

LONG-TERM PERIODICITIES IN THE JOVIAN DECAMETRIC EMISSION

By
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Ad Majorem Dei Gloriam

y para las Tias

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Observations of the decametric radio emissions from Jupiter have been made regularly for 39 years at the University of Florida Radio Observatory. In this dissertation, the very large data set that has been accumulated from these observations is used in an investigation of long-term variations in the occurrence probability and average flux density of the radio emission. The predominant periodicity that was detected was on a time scale of about 12 years, which is the period of Jupiter's orbital motion about the Sun. Previous suggestions that this periodicity is a geometrical beaming effect caused by the periodic variation in D_E , the Jovicentric declination of Earth, were verified and further developed. The D_E effect was found to be greatest for Jovian source non-Io-A. A rotating beam model for this source was developed which provided a good fit to the observed effect. The periodic D_E effect was also found to be present in the Io-related sources Io-B, Io-A and Io-C, but to a considerably smaller extent than in non-Io-A. The analysis of this data set also indicated a possible relationship with sunspot number, which has a periodicity varying

between 10 and 12 years, but more observations will be necessary before this relationship can be verified. Other investigations included a much needed revision of the widely used previously established boundaries (in terms of central meridian longitude and Io phase) of the major Jovian decametric sources, and a measurement of the elongation effect, i.e. the variation of occurrence probability with respect to Jupiter's elongation angle from the Sun.

CHAPTER 1 INTRODUCTION

1.1 The Discovery of Jovian Decametric Radio Emissions

The study of planetary magnetospheres outside of our own began in 1955 with the discovery of radio emissions from Jupiter at a frequency of 22 MHz by Bernard Burke and K. L. Franklin [1955]. They found during a drift scan of the sky near the Crab Nebula that a source of intermittent interference in the cosmic background noise records always occurred at the same sidereal time. Over the course of three months this source slowly drifted in sidereal time. After checking an ephemeris, they found that the position of Jupiter coincided with the location of this source in the sky [Franklin, 1959]. Soon after the announcement of radio emissions from Jupiter, C. A. Shain [1956] was able to confirm these observations from ones he had made at 18.3 MHz from Australia, and found that Jupiter activity had been present on records he had made in 1950. Shain found that the occurrence of Jovian activity tended to recur at intervals about equal to the so-called System II period used by optical astronomers. Gardner and Shain [1958] further refined the analysis of the longitude effect and identified one primary source and two secondary sources of Jovian decametric (DAM) emission. The three sources remained fixed in longitude relative to one another. All three sources, however, were found to drift in longitude relative to the System II period. Subsequently, several observers used measurements of the mean drift rate over intervals of several apparitions of the planet to obtain apparently precise measurements of the rotation period. Gallet [1957] found the rotation period of the radio sources in data taken at 18 and 22 MHz to be about

10 seconds shorter than the System II period of 9 hours 55 minutes 40.6 seconds. Carr *et al.* obtained a similar value from their observations. They defined a rotating Jovian longitude system called System III, which has a period of 9h 55m 28.8s, and coincided with System II at 0h UT on January 1, 1957 [Carr *et al.*, 1958]. They later revised the System III period to 9h 55m 29.35s [Carr *et al.*, 1961]. Using data from decimetric as well as decametric observations, the International Astronomical Union [1962] approved the System III (1957.0) period as 9h 55m 29.37s.

Observing Jupiter through a telescope all one can see of Jupiter are bands of clouds; there is no solid surface on which to track permanent features as the planet rotates. The only "feature" of some permanence is the Great Red Spot which has existed as a distinct cyclone for at least 300 years, but it drifts erratically in any longitude system that can be devised. The belts and zones of light and dark colors rotate differentially and never at a constant rate. Observers have classified for convenience two longitude systems in which to specify cloud locations in different regions of latitude, but none of the clouds remain stationary in either of the two systems. Clouds in the equatorial region of the planet are assumed to move at a rate specified by the System I longitudes. These features rotate through 360° of longitude in 9 hours 50 minutes. The more temperate regions of the planet generally follow the System II longitudes and have a period some 5 minutes longer than in the equatorial region. By specifying a zero longitude along the central meridian on some date and using the appropriate longitude system the *central meridian longitude* (CML), or the sub-Earth longitude, for any future date can be determined. With neither of these systems was there any way to be sure at what rate the inner, supposedly solid, body of the planet was spinning.

The discovery of the DAM and the realization that the main source (source A) could be used as a “landmark” (*i.e.*, a relatively permanent and regularly appearing radio feature) gave observers for the first time a means to study something located in the interior of Jupiter. Once it was determined that the DAM had its origins in the magnetic field of the planet, a fixed field which was generated within the interior of the planet, these landmarks could be used to establish a constant and meaningful rotation rate. Rotation periods based on Jovian decametric observations have been found to be very stable for more than 30 years [Higgins, 1996].

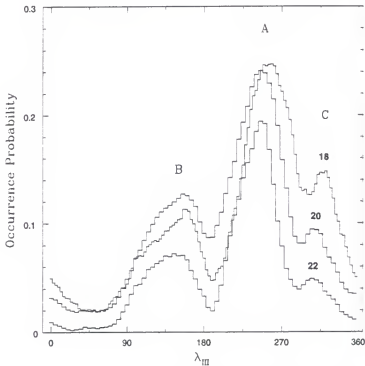


Figure 1.1: Occurrence probability versus System III (1965.0) Central Meridian Longitude for data spanning the years 1957–1994. The three histograms are from the 18, 20 and 22 MHz Yagi antennas. Of the three frequencies, the highest overall occurrence probability is at 18 MHz. The three strongest decametric sources A, B, and C are labeled.

A plot of a measure of the likelihood of detecting DAM versus Jovian longitude shows three peaks which have come to be known as “sources.” Current theories assume that they are not distinct sources, but instead may be due to rotating beams from a single

source, or perhaps from two sources located in opposite Jovian hemispheres. The sources have been designated A, B and C although in some literature they may be referred to as Main, Early and Third, respectively. The standard way of characterizing the location of these sources is in terms of the central meridian longitude (CML). The measure of likelihood of detecting DAM is referred to as the occurrence probability. It can be computed by dividing the number of hours of DAM activity detected by the number of hours of listening. The occurrence probabilities of detecting DAM even in the center of the sources are rarely more than 20%. More details on computing the occurrence probability are given in Chapter 2. A plot of occurrence probability versus CML is given in Figure 1.1. The DAM can be further characterized by the location of the Galilean satellite Io in its orbit. Bigg [1964] discovered that the 3 major DAM sources are strongly influenced by the departure of Io from superior geocentric conjunction, or the Io orbital phase from superior geocentric conjunction. The DAM sources which are influenced by Io are known as Io-A, Io-B and Io-C. Each source also has a non-Io related component as well as an Io-related one. A plot of the DAM sources in CML-Io phase space is given in Figure 1.2. Also visible in CML-Io phase diagrams at frequencies below about 18 MHz is the Io-D source. Io-D is located at similar longitudes to the Io-B source but at somewhat higher Io phase.

Carr *et al.* [1958] noted the existence of a very pronounced eight-day periodicity of Jovian radio emissions. All attempts to explain this effect by means of a correlation with sunspot number or terrestrial observing conditions turned up negative. A possible effect by the satellite Ganymede on the Jovian radio emission was also considered, since the orbital period of this satellite is about 8 days, but no convincing evidence was found that Ganymede was responsible. The explanation of the 8-day periodicity was not forthcoming until after Bigg's momentous discovery of Io control. The 8-day cycle of Carr *et al.* turned

out then to be the beat frequency between the roughly 10 hour Jovian rotation period and the 42 hour Io orbital period.

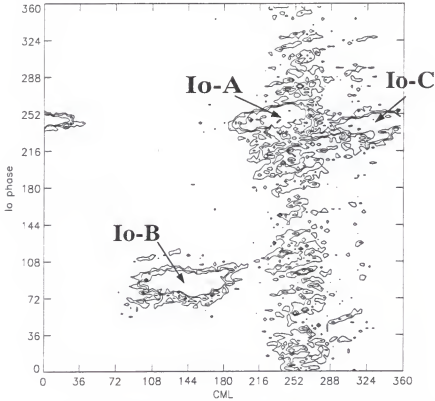


Figure 1.2: A plot of occurrence probability at 18 MHz for the years spanning 1965–1992. The Io-related sources are labeled. Non-Io A is the vertical line at central meridian longitude of approximately 252°. Non-Io C is weakly visible at about 324° CML. The CML and Io Phase range for these sources are given in Table 1.1

1.2 Polarization of DAM

Another characteristic of the decametric radio emission is its strong circular, or sometimes elliptical polarization. Franklin and Burke [1956] found most of the radiation to be right-hand circularly polarized, although one event was seen with mixed left- and right-hand circular polarization. Gardner and Shain pointed out that these polarization results imply the presence of a magnetic field. This was the first indication of a planetary magnetic field outside of Earth. It is now known that the emission is almost 100% elliptically or circularly polarized, in the right-hand sense for sources A and B, and often

in the left-hand sense for source C. The dominant polarization sense for each of the DAM sources is given in Table 1.1. The emission is believed to be radiated in the right-hand fast X-mode at a frequency just above the local electron gyrofrequency. The C source tends to be right-hand polarized at the low longitude edge of the source but becomes increasingly left-handed with longitude [Kennedy, 1969]. The A and B sources remain right-handed over all the frequencies studied.

Table 1.1: Various characteristics of the DAM sources.

Source Designation	CML range	Io Phase range	Maximum frequency (MHz)	Dominant Polarization
lo-D	0°—200°	95°—130°	18	LH
lo-B	105°—185°	80°—110°	39.5	RH
non-lo-B	80°—200°	0°—360°	38	RH
lo-A	200°—270°	205°—260°	38	RH
non-lo-A	230°—280°	0°—360°	38	RH
lo-C	300°—20	225°—260°	38	RH and LH
non-lo-C	300°—360°	0°—360°	32	RH and LH

from Carr *et al.*, 1983.

1.3 Frequency Dependence of Jovian Radio Emissions

The discovery of a decimetric wavelength nonthermal component of the Jovian radio spectrum (DIM) provided further insights into the Jovian magnetic field [Sloanaker, 1959]. This radiation was found to have a large linearly polarized component, a relatively flat spectrum and to have an emission region centered on Jupiter but extending about 2 Jovian radii on either side of the planet. It was soon recognized that this emission implied a population of high energy electrons trapped in a magnetic field and emitting

through the synchrotron process. The discovery of these Jovian radiation belts occurred nearly at the same time that Earth's Van Allen radiation belts were discovered [Van Allen *et al.*, 1958]. A characteristic of the DIM emission is that the plane of polarization of the linear component varies sinusoidally with about a 10 hour period and an amplitude of $\pm 10^\circ$. This variation in the orientation of the polarization plane was evidence of a predominantly dipolar magnetic field, the axis of which is tipped by 10° from the rotation axis of the planet. There are many review articles on the synchrotron component of the Jovian radio emission [Roberts and Komesaroff, 1965, Carr and Gulkis, 1969, Carr *et al.*, 1983]. Studies of the polarization of the decametric radiation found that the right-hand polarized component had a maximum frequency of nearly 40 MHz while the left-hand component only reached 28 MHz. Assuming the radiation is emitted in the right-hand extraordinary mode at frequencies just above the local electron gyrofrequency, the Jovian magnetic field strength at the source could be estimated. Since the gyrofrequency in MHz is approximately 2.8 times the magnetic field strength in Gauss, the 40 MHz and 28 MHz maxima for the right-hand and left-hand components, respectively, imply maximum magnetic field intensities of at least 14 Gauss in the northern magnetic hemisphere and 10 Gauss in the southern. The magnetic north pole is located in the northern hemisphere, opposite that of Earth. These two maximum field intensities together with the observation that the north end of an assumed magnetic dipole is tipped by about 10° toward the System III longitude of 200° can define an *offset tilted dipole* (OTD) model of the field. Although this was a good first approximation to the true field distribution, later *in situ* measurements by Pioneer and Voyager spacecraft demonstrated that there are also strong quadrupole and octupole components (and probably higher multipole components as well) [Acuña *et al.*, 1983].

The Jovian decametric emission is now known to extend from a sharp high frequency cutoff of 39.5 MHz to a rather indistinct low frequency cutoff of 3 MHz where it merges into the hectometric (HOM) emission [Carr *et al.*, 1983]. The peak flux occurs at about 8 MHz. A spectrum of the Jovian radio emission illustrating the intensities and extent of the decimetric, decametric, hectometric, and kilometric (KOM) regions is given in Figure 1.3. The lowest frequency that ground-based observers can detect during years of low sunspot number is about 10 MHz. Lower frequency observations have been made by Earth-orbiting satellites and by the Voyager flyby missions. The lowest frequency detected in the KOM band is just above the plasma cutoff frequency of the interplanetary medium. At the high frequency end of the decimetric emission region thermal emission from Jupiter starts to become the prevalent source of radio noise.

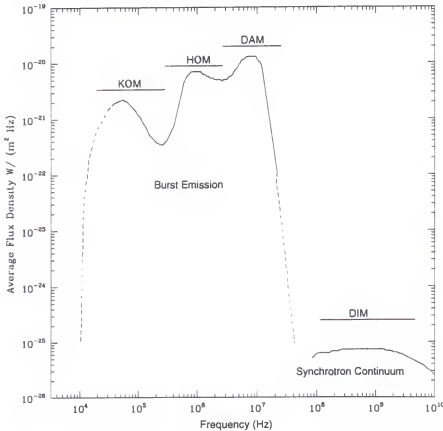


Figure 1.3: Average radio power flux density spectrum with band designations from [Barrow and Carr, 1992]. High and low end cutoff frequencies are explained in the text.

1.4 The Jovian Emission Beam Model and the D_E Effect

After 1961, occurrence probability histograms appeared to indicate a rotation period for the decametric sources that was about 1 second longer than that of System III (1957.0) [Douglas and Smith, 1963, Smith *et al.*, 1965]. Gulkis and Carr [1966] recognized that this drift in the longitude of the sources had both a secular and a cyclic component. When they assumed that the cyclic error component had a period of about 12 years, they were able to show that the secular component of the rotation period measurement was about +0.3 seconds. They demonstrated that the cyclic error was most likely due to the fact that D_E , the Jovicentric declination of Earth, was significantly different at the beginning and ending times of the interval (several years long) over which the average value of the rotation period was measured. The cyclic error component was first thought to be due to changes in solar activity since the period and the phase of this drift was in near anti-correlation with the solar cycle (about 11 years). The period of the drift was also close to the orbital period of Jupiter (11.86 years). One quantity that varies with the Jovian orbital period is the Jovicentric declination of Earth or D_E . Jupiter's axis is inclined by 3.1° to a perpendicular to its orbital plane. Jupiter's orbital plane is inclined by 1.3° to Earth's orbital plane [Bishop, 1995]. The combination of the two effects causes Earth to vary in Jovicentric declination by $\pm 3.3^\circ$. D_E varies with the 11.86 year orbital period of Jupiter as well as the 1 year period of Earth in its orbit. The D_E effect is a geometrical one, resulting from the fact that the ground-based radio observers see different parts of a narrow emission beam that corotates with Jupiter during different apparitions of the planet, and therefore an error will be made in assuming that the longitudes of the radio source peaks at the first and last apparitions were the same. An important conclusion from Gulkis and Carr [1966] was that the cyclic error in rotation period measurements can be largely eliminated by selecting a pair of apparitions having mid-dates that are

about 12 years apart for the observations, so that the average D_E for the two apparitions will be approximately the same. At the time however, there were insufficient data to completely rule out a solar anti-correlation on the drift in the decametric sources.

The results of Gulkis and Carr were substantiated and enlarged upon by Dulk [1967] and Carr *et al.* [1970]. Dulk found in the dynamic spectra that the drift of the main (A) source and the early (B) source were in opposite directions. He concluded that the decametric emission was sharply beamed into a thin, conical sheet. The divergence of the sources with D_E was due to changing perspective as Earth moved into higher Jovian latitudes. A southern hemisphere cone should also be visible from Earth according to Dulk's model, but due to asymmetries of the Jovian magnetic field from a perfect dipole, this cone is not oriented such that any edge of the cone reaches Earth [Dulk, 1967].

The first thorough investigations of higher-order multipole-components of the Jovian magnetic field came with the Pioneer 10 and 11 missions. In 1973, Pioneer 10 and in 1974, Pioneer 11 made the first *in situ* measurements of the magnetic field and embedded plasmas in the Jovian system. The Pioneer 11 spacecraft in particular was able to provide detailed information on the Jovian magnetic field since it passed within 1.6 Jovian radii (R_J) of the planet [Acuña *et al.*, 1983]. Both spacecraft found the Jovian magnetosphere to be an immense structure of about 100 R_J on the sunward side. The magnetotail was detected by the Voyager spacecraft out to about the orbit of Saturn, 5 AU distant [Desch, 1983]. If the magnetosphere were visible, it would appear from an observer on Earth to be larger than the full Moon. The mainly dipolar shape of the magnetic field is severely distorted outside of 6 R_J due to trapped charged particles forming an equatorial current disc. This disc causes the field lines to have a much larger radial component along the magnetic equator. From the Pioneer and Voyager spacecraft data several models of the Jovian magnetic field have been built. Since all of the spacecraft were on flyby missions,

the sampling of the magnetic field over latitude and longitude is far from complete. This allows for a family of different models to be proposed all of which may adequately fit the data. One of the models proposed that best fit the observed data was the O_4 model [Acuña and Ness, 1976]. Using data from the magnetometer on board Pioneer 11, this model included terms up to octupole for the field generated within the planet. The external magnetic field due to the current disc was assumed negligible. A newer magnetic field model is the O_6 model which uses weighted observations from Pioneer 11 and Voyager 1 [Connerney, 1992]. This is also a multipole expansion to the octupole term but provides for the existence of higher orders [Connerney, 1993]. This model is in the process of being modified due to new observations of the Io flux tube footprint made in the infrared [Connerney *et al.*, 1993].

1.5 Observing Jovian Decametric Radiation

Perhaps the first thing one notices when making ground-based observations of DAM is how bursty the emission is. The radio emissions appear in "storms" of perhaps an hour or less. The interplanetary medium impresses a scintillation effect upon the emission so the radio noise will fade in and out over several seconds. Earth's ionosphere will also cause scintillation of the DAM emission. The DAM by its nature is intermittent and there are large variations in intensity during one event. Observers have classified two types of DAM emission bursts, long or L-bursts and short or S-bursts. L-bursts appear as wide bandwidth (few MHz), amorphous emission regions when displayed on frequency-time spectrograms, or dynamic spectra. L-bursts usually last several seconds and when the radio noise is played over a loudspeaker sounds like waves crashing on a beach. L-bursts often display the effects of terrestrial and interplanetary scintillation as well as modulation lanes. Riihimaa [1970] discovered that in some dynamic spectra,

modulation lanes appear as alternate stripes of increased and decreased emission that drift by about 150 kHz/s, and can have either positive or negative slopes. Imai *et al.* [1992] have proposed that modulation lanes in observed dynamic spectra represent frequencies and times of constructive and destructive interference produced as wide-band decametric emission passes through an interference screen located near Io's orbit at 180° from superior geocentric conjunction. L-bursts observed near the planet might be several seconds to minutes long, their dynamic spectra often exhibiting the arc structure of the DAM seen in dynamic spectra taken by Voyager. On propagating through the nonuniform interplanetary plasma on its way to Earth, these initial long L-bursts are broken up by interplanetary scintillation into the shorter L-bursts (1 to 10 second duration) that we actually observe. The modulation lanes are still present, but have large gaps caused by the fading of intensity between successive L-bursts. S-bursts have only been observed with the Io-related sources. S-bursts are repetitive sequences of short-duration frequency-drifting pulses having lifetimes less than 100 msec each. Each pulse has significant structure on time scales down to a very few microseconds (Carr and Reyes, private communication). The frequency drift of these S-burst pulses varies from 5 to 45 MHz/sec always from high to low frequencies. S-burst dynamic spectra on timescales of milliseconds can exhibit remarkably varied structure [Flagg *et al.*, 1991].

1.6 Discussion of the Problem

The emission beam model that is now used to explain many of the characteristics of the DAM is very similar to that developed by Dulk [1967]. The "sources" are the edges of a thin, hollow cone fixed to field lines running through the center of the planet and rotating with the planet in a little under 10 hours. The latitudinal effect provides information on the east-west width of the cone and the cone thickness. The A and B

sources are the trailing and leading edge of a cone located in the northern hemisphere and just above the ionosphere of the planet. The C source may be one edge of a southern hemisphere cone but that is still uncertain.

The latitudinal effect on the DAM provides information on the north-south extent of the emission beam. This effect depends on the slowly changing declination of Earth in Jovicentric coordinates. Since one Jovian orbit about the Sun is nearly 12 years it is necessary to study several dozen years of data in order to understand the latitudinal control of the Jovian decametric emission. The University of Florida Radio Observatory is unique in being able to provide a data set which spans several Jovian years (12 Earth years each) and allows one to thoroughly study how DAM changes with the Jovicentric declination of Earth. The result of this analysis will be an improved understanding of the shape of the emission beam. A second consequence of studying these long term variations in DAM is to enable one to find solar influences on DAM which may vary with the roughly decade long solar sunspot cycle. In Chapter 2 a description is given of the data reduction method and of the method whereby variations in the DAM due to orbital viewing geometries and changing galactic background levels are removed. Chapter 3 is a study of the latitudinal control of the DAM and a search for any long-term solar effects. Chapter 4 will summarize what these results may mean for the shape of the DAM emission beam and the changes the source region may undergo over the course of a solar cycle.

CHAPTER 2

METHODS

Time: 330 Started watch period. Occasional very faint static-like bursts. No station interference. Set clock with recorder. Killed scorpion.

—portion of log from Thomas D. Carr, January 8, 1957 during the first week of observation taken at the University of Florida Radio Observatory

2.1 Data Collection

The radio observations used in this study were taken by antennas located at the University of Florida Radio Observatory (UFRO) and at the Maipu Radio Astronomical Observatory (MRAO) in Chile. Radio observations at the University of Florida began on December 31, 1956. The station was located on the campus of the University of Florida near the current location of the University Public Safety office. In 1962 the observatory was moved to the northern shore of Bivens Arm lake in Gainesville. In the fall of 1967 the UF Radio Observatory was moved to a site near Old Town in Dixie County, Florida. The data from MRAO are added to the Florida data in the 1959 through 1965 seasons.

The UFRO 18, 20 and 22 MHz data were taken using Yagi antennas connected to Collins 75S-1 receivers. The receiver bandwidth was 5 kHz. The audio output signal was sent to Texas Instruments chart recorders, Brush chart recorders and to audio loudspeakers. Timing marks were recorded automatically from signals received from WWV. The most important component of the data collection process is the observer. It is up to the observer to listen to the signal over the loudspeaker and discriminate between Jovian decametric radio noise and interference of various kinds. When Jupiter is recognized over the loudspeakers the observer will note the deflections due to Jupiter on the chart record. Immediately after the Jupiter noise "storm" the observer will calibrate against a noise

generator all the channels in which Jupiter noise was present. The noise generator used since the 1965 apparition is a Hewlett-Packard 461A amplifier. The HP 461A has been found to have a very broad and flat noise spectrum at the decametric radio frequencies. The HP 461A is occasionally calibrated against a pair of type 5722 noise diodes that serves as the standard noise source. The observer keeps a log of the start and stop times of the watch, observing conditions, and other information pertinent to the maintenance of the observatory and the further reduction of the chart records. Every half hour the observer will indicate the observing conditions for each frequency channel. The standard notation for observing conditions has been a scale from 5.0, for perfect conditions with no interference, to 0.0, where interference is so high that practically no Jupiter radio noise could be detected over the interference. Determining observing conditions for moderate interference has been a subjective matter quite dependent on individual observers. The importance of observing conditions to the determination of occurrence probabilities will be addressed in the data reduction section.

2.2 Data Reduction

2.2.1 Standard Format

The format used for reading files into computer programs has changed considerably over the years. The use of punch cards for programming and data entry made an 80 column format for the Jupiter data reduction the best choice. A review of the column designations for various stages of the data reduction can be found in Thieman [1977]. Later data sets were reduced without the need for punch cards. The method by which a chart record of a night's observation is entered as a computer file begins by entering the start and stop times for the watch, any Jupiter activity and any interference intervals during the night. For nights in which Jupiter was detected, the peak Jupiter deflections

for every five minute interval as well as the deflections due to the galactic background immediately before and after the Jupiter radio storm are noted. The deflections due to various attenuations of a standard noise generator are also recorded. A new format was used for data taken from 1981 through 1992 [Higgins, 1996]. Earlier data sets have also been converted into this one format. A sample of the data format is given in Figure 2.1.

```

$
#123081.18y      filename
123081           date
18y             frequency & antenna
808             begin watch hour minute (all times UT)
1137            end watch hour minute
1               number of storms
809             begin storm
829             end storm
1               number of interference intervals
1100            begin interference interval
1130            end interference interval
x               type of interference (x=static, s=stations, b=buzz)
18.00           galactic background deflection at start of storm
1               calibration number
4               number of 5 minute intervals
809             start of first 5 minute interval
70.00           deflection of highest Jupiter peak in interval
814
32.00
819
22.00
824
28.00
15.00           galactic background after storm
$
c1123081.18y    calibration filename
123081           date
18y             frequency & antenna
1               calibration number
7               number of calibration steps
59              first decibel attenuation of noise generator
3.00            chart deflection corresponding to decibel attenuation
37
14.00
35
20.00
32
31.00
29
47.00
26
68.00
23
93.00

```

Figure 2.1: A sample of the format developed by Higgins for the reduction of the Jupiter synoptic monitoring program data.

2.2.2 Occurrence Probability

One of the fundamental parameters used to study the Jovian decametric radiation is the amount of activity detected over a given time period. The occurrence probability is

a common indicator of this activity. Occurrence probability is given as

$$OP = \frac{\text{Number of hours of Jupiter detected}}{\text{Number of hours of listening}} \quad (2-1)$$

For an accurate estimate of the occurrence probability one needs to know when the observers were actually "listening." Listening is defined as the condition where all instruments are operating; the observer is listening to the speakers for any Jupiter noise and interference, if present, is not bad enough to prevent the observer from determining if Jupiter noise is present. How much interference is "too much" depends on many factors. If the Jupiter noise storm is very strong, almost no amount of interference will prevent an observer from detecting it. With moderate interference and moderate levels of Jupiter noise, listening becomes dependent upon the skills of the individual observers to distinguish Jupiter noise. For those who reduce the Jupiter data, these factors must be taken into account for accurate occurrence probabilities to be computed. Personnel reducing the data will use the observing condition records written in the log book and the chart records themselves in order to determine the amount of listening. For this study, the data sets which include "interference intervals" are time periods when observing conditions were given as less than 1.0, conditions where the interference is so intense that no Jupiter could have been detected had it been present. This might be an overly conservative estimate of the interference intervals but because no systematic scaling of more moderate levels of interference had been made and because of the varying skills of the observers, it is very difficult to gauge where the cutoff would be. An assumption that has to be made when discussing occurrence probability is that the listening times chosen were completely independent of Jovian longitude and Io orbital location. Since ephemerides can provide times when certain configurations of central meridian longitude and Io phase will take place, this information can not be used to plan observations if the occurrence probabilities generated from these data are to be free of bias.

To build up accurate statistics on the occurrence probability of Jovian decametric emission, several conditions must be met. The first condition is that the catalog be of observations made by instruments with similar sensitivities. This condition is satisfied in this report by making use of data taken only from Yagi antenna systems. The antennas, the cables, the receivers and the recorders have been of a consistent type and quality over the span of the data set used in this study. The rest of the conditions deal with the manner in which the data are reduced. Besides accurate estimates of the amount of listening time, accurate estimates of the completeness of the data in terms of the intensity of the Jupiter noise must be made. The likelihood of detecting weak Jupiter pulses is a function of many factors including the listening conditions at the observatory. Both the local time and solar activity affect the density of the Earth's ionosphere over the observatory and thereby the listening conditions. Weak pulses may also not be detected if Jupiter is observed during times when it is located closer to the galactic plane. The galactic background radio noise will raise the minimum detectable flux density and subsequently reduce the amount of weak Jupiter pulses detected. The detected radio emission from Jupiter also follows a $\frac{1}{r^2}$ dependence in intensity. During any one observing season the distance to Jupiter may vary by nearly 2 astronomical units and can also contribute to changes in the likelihood of detecting weak Jupiter bursts. All of these factors need to be accounted for before a meaningful discussion on variations in the occurrence probability can be made.

2.2.3 Weekend versus Weekday Observers

An inspection of data taken during the late 1980s at the UFRO turned up significant differences between the occurrence probabilities computed using only weekend observations and those using data taken during the week. It appears that from 1984, when a new weekday observer was hired, through the end of the data set used in this project the weekend observers detected more Jupiter radio emissions per unit listening time than

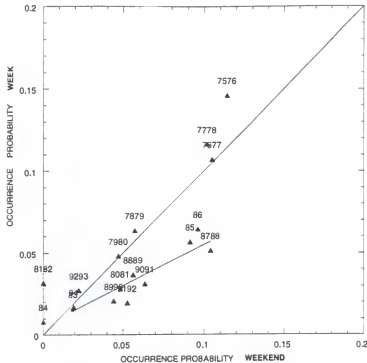
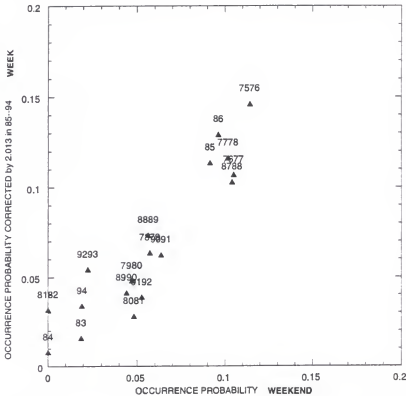


Figure 2.2: A bias found in the amount of activity observed during weekday watches versus that found in weekend watches. The points are labeled with the season over which the data is averaged. Label 8788 is for the 1987-88 season. The 45° line represents equal amounts of activity detected during weekend and weekday watches. The lower line represents the best fit to data from 1985-1994.

the weekday observer. Previous to 1984 the occurrence probabilities for weekend and weekday observations were nearly identical. In order to correct for the bias introduced by this disparity, a plot of weekend average occurrence probability for each season versus the weekday occurrence probability was made. On this plot all seasonal occurrence probabilities which were identical for weekend and weekday observers should lie on a 45° line. An example of this plot using data taken at 18 and 20 MHz from 1975 through 1994 is shown in Figure 2.2 The biased apparitions have a different distribution than the unbiased apparitions. A linear best-fit to the biased data from 1984–94 provided the slope which was used as a correction factor to the data. The total amount of activity that the weekday observer recorded each apparition is multiplied by a correction factor which is the inverse of the slope of this best fit line. This would increase the weekday occurrence

probabilities for the apparition to a level roughly equivalent to the weekend occurrence probability. In this correction it is assumed that the weekend occurrence probabilities reflect accurately the true occurrence probability for decametric emission detected by our ground-based instruments. The correction factor for the weekday activity for 18, 20 and 22 MHz is 2.013. Figure 2.3 is a plot showing apparitions from 1975 to 1983 and the bias corrected apparitions from 1984 to 1994.



months until opposition at 18 MHz is given in Figure 2.4. The figure shows that the occurrence probability increases as Jupiter approaches opposition but that the degree to which the occurrence probability drops away from opposition is not symmetrical about zero. The months before opposition generally have a higher occurrence probability than those months after opposition. Before opposition Jupiter transits in the early morning hours when the terrestrial ionosphere has thinned and radio interference is at a minimum. These good observing conditions will often last until sunrise. After opposition Jupiter transits in the evening. Observing conditions can be quite poor in the hours immediately after sunset when the terrestrial ionosphere is still quite dense and interference from radio stations can be strong. The density of the terrestrial ionosphere is strongly influenced by the sun. The average electron number densities in the ionosphere show a day-night periodicity and a periodicity based on the solar cycle. During times of high sunspot number the ionosphere is denser than during low sunspot number. In Figures 2.5 and 2.6 the monthly occurrence probabilities for years of low and high sunspot number are plotted. The seasons of low average sunspot number are those from 1961–1966, 1972–1978, 1983–1988 and 1992–1994. The seasons of high average sunspot number are 1957–1960, 1967–1970, 1978–1982, and 1988–1992. A significant difference in the plots is the larger amount of asymmetry between pre- and post-opposition occurrence probabilities in the plot made during years of high sunspot number. This asymmetry illustrates the strong influence solar activity has on the observing conditions at these frequencies. The difference in the overall levels of activity between the two plots will be discussed in Chapter 3 in the context of the D_E effect on the DAM.

The interplanetary medium also influences the detection of Jovian decametric emission. The DAM scintillates as it passes through this medium and causes the bursts to be modulated strongly with a period of a few seconds. Genova and Leblanc [1981] find

that the amount of scintillation is reduced around the time of opposition. This is due to the interplanetary plasmas moving roughly along the line of sight so their tangential velocities are very small. Any density inhomogeneities would take longer to cross the observer's line of sight.

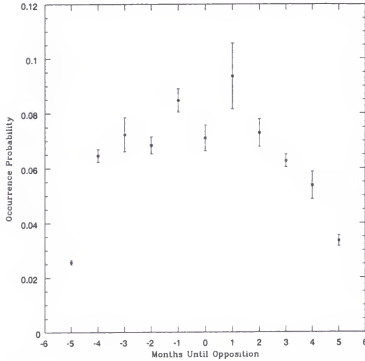


Figure 2.4: A plot of the monthly occurrence probability for 18 MHz Yagi observations from 1957–1994. Data are binned by the number of months before or after the opposition date for each year. Error bars are 1 standard deviation for the scatter around the mean represented by the point in each bin.

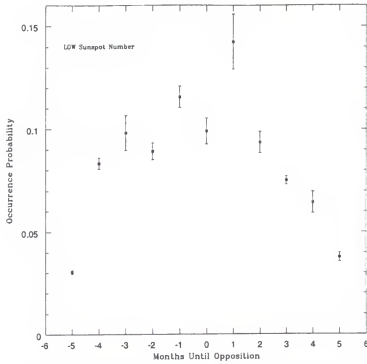


Figure 2.5: Plot of monthly occurrence probabilities at 18 MHz centered on the month of opposition for those years during which the sunspot number was low.

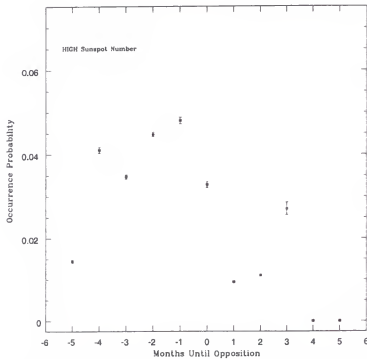


Figure 2.6: Plot of monthly occurrence probabilities at 18 MHz centered on the month of opposition for those years during which the sunspot number was high.

2.2.5 Galactic Background and Distance Effects

The sensitivity limit of our instruments is primarily determined by the galactic background level. This limit is often expressed in terms of the minimum detectable antenna temperature. The effects that changes in galactic background and distance have on the minimum detectable antenna temperature need to be accounted for before an analysis of long-term variations in DAM can be performed. In other words, some threshold temperature must be set that will allow one to compare seasons for Jupiter activity levels free of influence from the galactic background. Another influence on the apparent galactic background temperature comes from the orientation of the antenna with the ground. Since the data used in this study are from Yagi antennas which track Jupiter across the sky, the configuration of the antenna with respect to the ground will change and this will change the apparent galactic background levels. In other words, if a radio storm takes place while Jupiter is at a low altitude, part of the antenna beam may be pointing towards the ground so the background levels will be less than when the storm takes place while Jupiter is near transit.

As Jupiter orbits the Sun the ground-based observer sees Jupiter set against different parts of the galactic background. Over one 12-year period Jupiter enters regions of the sky close to the galactic center and to regions near the galactic poles. The average value of the galactic background across the beam-width of the Yagi antenna will reflect these changes. Figure 2.7 illustrates the large changes in the seasonal average galactic background antenna temperatures measured at 18, 20 and 22 MHz with Yagi antennas. The highest peaks in 1972 and 1984 occur during passage of Jupiter near the galactic center and are nearly four times the minimum values. The secondary peaks in 1978 and 1990 occur when Jupiter passes through the galactic plane in the anti-center direction.

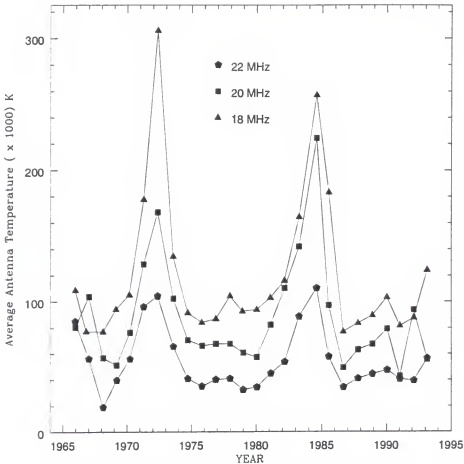


Figure 2.7: A plot of the average background antenna temperature measured at 18, 20 and 22 MHz with Yagi antennas. The largest peaks occur when Jupiter crosses the galactic equator near the galactic center, the smaller peaks occur when Jupiter crosses the galactic equator in the anti-center direction.

Besides the twelve year period of galactic background changes there is a yearly variation in the Earth-Jupiter distance. The relative distance of the two planets can change by almost 2 astronomical units over one observing season. Both the changes in distance and galactic background are expected to influence the occurrence probability. As the distance from Jupiter increases over one season, a certain fraction of those bursts which would have been detected around opposition would drop below the detection threshold of the Yagi antennas. The occurrence probability would be lower during years of high galactic background levels since weak Jupiter that would be detected when background levels were low now would be lost in the noise.

If T_A is the antenna temperature for a given frequency channel due to Jupiter and the galactic background and T_G is the contribution due to the galactic background alone, then the contribution due to Jupiter is $T_J = T_A - T_G$. The noise temperature of the receiver is negligible in comparison to T_G . The sensitivity of the radio telescope for detecting Jupiter activity is thus limited by the galactic background temperature, which is different in different apparitions. For long-term comparison of occurrence probability, the system sensitivity must remain constant. It was therefore necessary to establish a standardized value of minimum detectable Jovian antenna temperature, $T_{\min}$, defined for the apparition during which the galactic background temperature was highest. In all other apparitions one would reject all pulses of Jovian antenna temperature less than $T_{\min}$. That is, whenever T_J is less than $T_{\min}$, the Jovian activity is assumed to be zero.

The minimum detectable antenna temperature was estimated by plotting a number distribution of antenna temperatures for bursts over the course of one season. Figure 2.8 shows a number distribution for the antenna temperature of Jupiter bursts above galactic background at 18 MHz for the 1986 season. This season had a very low average galactic background temperature. This figure shows that the counts increase towards lower antenna temperatures until a peak is reached. This turnover point in our distribution is where we can no longer detect all bursts. A certain fraction of the bursts at such a low antenna temperature will be hidden in the noise and the observers may not be able to distinguish these pulses as DAM. The minimum detectable antenna temperature is estimated from this curve to be about 10,000 Kelvin. This value is for years of low galactic background temperature.

In Table 2.1 are the average galactic background temperatures for each season at 18, 20 and 22 MHz using a Yagi antenna of beamwidth approximately 50° . The method by which we account for both the galactic background changes and the changing Earth-

Jupiter distance is as follows. The average of the three highest background temperatures is designated $T_{\max}$. Similarly the average of the three smallest temperatures is $T_{\min}$. $T_{\max}$ is the average of the temperatures from the 1972, 1984 and 1985 apparitions. $T_{\min}$ is the average of the 1986, 1967-68 and 1975-76 apparitions. The ratio $\frac{T_{\max}}{T_{\min}}$ describes how much higher the galactic background temperature is on average during years when Jupiter appears near the galactic center. The ratio is 3.132 for the 18 MHz Yagi. This ratio multiplied by 10,000 Kelvin represents the cutoff we will assume for the years of high galactic background. The minimum detectable antenna temperature is about 10,000 Kelvin at 20 MHz. The high galactic background temperature cutoff for the 20 MHz Yagi is 33,740 Kelvin. For 22 MHz the minimum detectable antenna temperature is 5,000 Kelvin and the high galactic background cutoff is 15,270 Kelvin. For those seasons in which no calibrations were performed, namely before the 1966 season and after the 1992–1993 season the corrected O.P. was estimated based on seasons 12 years earlier or later. Jupiter will appear with the same region of the galaxy in the background as it had one orbital period earlier or 12 years.

In order to correct for distance effects the background subtracted antenna temperature for each pulse was multiplied by a distance correction factor. That is

$$T_J^* = T_J \times \left(\frac{r}{r_{\min}} \right)^2 \quad (2-2)$$

where r is the distance to Jupiter in Astronomical Units at the time of each Jupiter storm and $r_{\min}$ is equal to 4 A.U. By selecting only those Jupiter bursts in every season whose distance corrected antenna temperature exceeds this cutoff, we will effectively simulate the effects of high galactic background noise levels for every season and correct for the changing Earth-Jupiter distance. This will of course reduce the amount of data used to compute the occurrence probability. Table 2.2 gives the occurrence probabilities for the

18 MHz Yagi using all of the activity data each season and the occurrence probabilities using the temperature cutoff of 31,320 Kelvin. Figure 2.9 shows the seasonal occurrence probability for all bursts detected by the 18 MHz Yagi and the occurrence probability with the distance and galactic background correction. The incentive to check the effect of galactic background levels on occurrence probability came when it was recognized that the rise and fall of the occurrence probability with D_E was asymmetric. That is, the occurrence probability tends to rise sharply with increasing D_E and drop more gradually. The peak in the galactic background occurs during the sharply rising period about 1 year after the minimum in D_E . Figure 2.9 shows that with the correction the trailing edges of the occurrence probability curves are reduced slightly more than the leading edge. The asymmetry was not completely removed however. The procedure for determining the background-limited occurrence probabilities is summarized in Table 2.3. An error was found in the program used to compute the background corrections. The distance correction was not performed on the antenna temperatures and the temperature cutoff was about 5% too high. Both of these errors caused too many pulses to be rejected and reduced the occurrence probabilities. The difference is small however, less than 7%. This error was corrected and all of the tables and plots in this chapter have been corrected however the occurrence probabilities used in the following chapters were not corrected for distance and have a cutoff temperature somewhat too high.

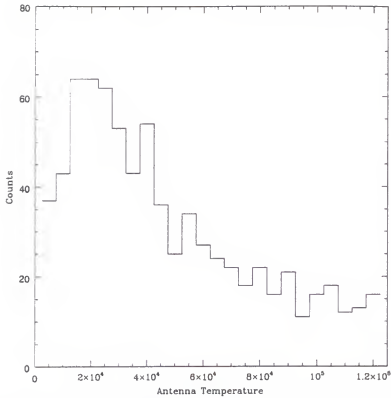


Figure 2.8: Number distribution of DAM bursts in 1986 at 18 MHz in terms of the temperature of each burst above the galactic background antenna temperature. This season had a low average galactic background antenna temperature.

Table 2.1: Seasonal averaged galactic background temperatures for 18, 20 and 22 MHz Yagi.

Season	18 MHz T_G	20 MHz T_G	22 MHz T_G
1965-66	108628	80489	84958
1966	77156	103818	56378
1967-68	77112	57107	19046
1968-69	94113	51484	39785
1969-70	105132	76532	56219
1970-71	177637	128563	96070
1972	305839	168039	104293
1973	134429	102242	65616
1974-75	91334	70490	40964
1975-76	84103	66185	35058
1976-77	86771	67644	40224
1977-78	104053	67603	41007
1978-79	92493	60818	32386
1979-80	93634	57406	34364
1980-81	102598	82104	44988
1981-82	115781	110138	53787
1983	164269	141848	88354
1984	256902	224300	110077
1985	183008	97038	57713
1986	76836	49432	34200
1987-88	83445	63003	40888
1988-89	89341	67353	44430
1989-90	103128	79084	47596
1990-91	81442	42978	40596
1991-92	87572	93690	39456
1992-93	124011	55735	56473

Table 2.2: Seasonal averaged occurrence probabilities for 18 MHz Yagi 1957-1975.

Season	Uncorrected O. P.	Corrected O.P.
		$T_{\min} = 31,320\text{K}$
1957-58	.03133	.03006
1958-59	.00820	.00812
1959-60	.05404	.02656
1961-62	.02309	.01945
1962-63	.12873	.11498
1963-64	.15170	.11530
1964-65	.07853	.05961
1965-66	.08658	.06456
1966	.07911	.07601
1967-68	.05000	.04872
1968-69	.04338	.04317
1969-70	.03362	.03263
1970-71	.00979	.00971
1972	.02790	.02790
1973	.06268	.06137
1974-75	.11146	.09666
1975-76	.15960	.13417

Table 2.3: Seasonal averaged occurrence probabilities for 18 MHz Yagi 1975-1994.

Season	Uncorrected O.P.	Corrected O.P.
		$T_{\min} = 31,320\text{K}$
1975-76	.15960	.13417
1976-77	.11883	.09511
1977-78	.12757	.11307
1978-79	.06612	.05890
1979-80	.05931	.05324
1980-81	.03919	.03654
1981-82	.02824	.02454
1983	.01720	.01582
1984	.02035	.01874
1985	.12662	.10330
1986	.15577	.11051
1987-88	.12304	.09891
1988-89	.09734	.07196
1989-90	.04639	.03665
1990-91	.08080	.06902
1991-92	.05077	.04244
1992-93	.05029	.04621
1994	.03207	.02660

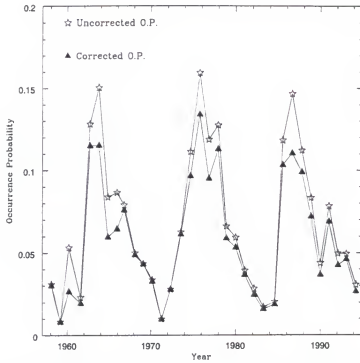


Figure 2.9: A plot of the occurrence probability for all the data collected with the 18 MHz Yagi. The curves are the uncorrected O.P., and the O.P. corrected for distance and galactic background effects.

Table 2.4: The procedures used to obtain galactic background-limited occurrence probabilities

Method for obtaining seasonal averaged occurrence probabilities
1. Determine the number of hours of listening. This includes deleting those times when the conditions went below 1.0 according to the observer's log and when the equipment was not functioning properly.
2. For each five minute interval of activity, determine whether the antenna temperature exceeded the interpolated galactic background found from the galactic background values taken before and after the radio storm, from this determine the galactic background subtracted antenna temperature, T_j .
3. Correct for changes in distance by multiplying each T_j by a correction factor.
4. Correct for changes in the galactic background levels, for seasons from 1966 through 1993. Sum only those five minute intervals of activity in which the distance corrected antenna temperature of the Jupiter burst, T_j^* , exceeds the threshold level.
5. For the seasons from 1984 through 1994, multiply the weekday activity time by 2.013 to correct for observer bias.
6. Divide the sum of activity over the season from step 3. (or 4 if the year is between 1984-1994) by the sum of the listening determined in step 1., this is the galactic background-limited occurrence probability.
7. For the seasons outside of the range 1966-1993 find a season 12 years later which does fall in the range and determine the ratio of the galactic background-limited occurrence probability to the occurrence probability without this correction. Multiply the occurrence probability for seasons outside this range by this factor.

2.2.6 Calibration Procedure

The first step in the calibration process is converting all of the chart record deflections into decibels of attenuation from a standard noise generator. Each chart record in which Jupiter was present should contain a calibration scale. The least-squares best fit is found to decibel attenuation and chart record deflection response. This provides a functional form for which one can determine for any deflection the corresponding decibel attenuation against the standard. The program used in this study tries to fit a fourth, third and second order polynomial to the calibration curve. Whichever fit had the smallest sum of squared residuals was chosen to describe the calibration curve. Figure 2.10 shows a typical calibration and the best fit curve. This function was used to convert the galactic background deflections into decibels. Each peak deflection for every 5 minute interval during the storm was also converted into decibels. In order to compute the antenna

temperature due to the galactic background and Jupiter the attenuation and gains in the line between the antenna and the calibration point must be known. Appendix A lists the line losses and gains for the 18, 20, 22 MHz Yagi antennas from 1981 through 1992. To subtract the galactic background noise from the Jupiter noise an interpolated galactic background is found by fitting a line to the two galactic background temperatures at either end of the storm interval. The antenna temperature of the galactic background, the antenna temperature of the highest peak each 5 minutes and the interpolated galactic background are shown in Figure 2.11 for a typical storm. The antenna temperature due to Jupiter alone is shown in Figure 2.12 where the antenna temperature for each 5 minute interval is subtracted from the interpolated galactic background for that interval. The flux density is found from the background subtracted antenna temperature, the antenna effective area and Boltzmann's constant. Appendix A provides an example of the method by which the Jupiter storms were calibrated.

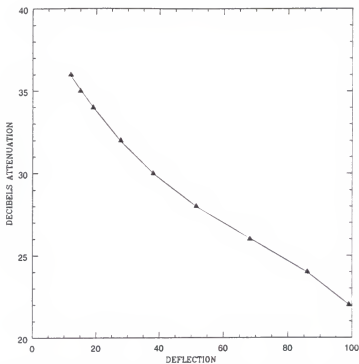


Figure 2.10: Sample calibration curve. The points are taken from a calibration done on June 1, 1987 for the 18 MHz Yagi. The best fit line is a fourth-order polynomial. The attenuation was off of a HP 461A noise generator with a noise temperature of 62.7 million Kelvin.

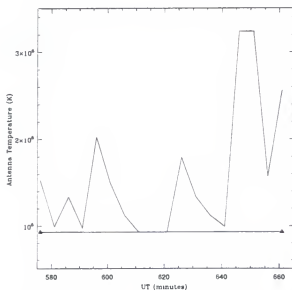


Figure 2.11: Plot of antenna temperature for the highest peak every 5 minutes. This storm was observed on June 1, 1987 with the 18 MHz Yagi antenna. The solid triangles represent the galactic background antenna temperature determined for the beginning and end of the storm interval. A first order polynomial was found from these two points and is shown in the figure.

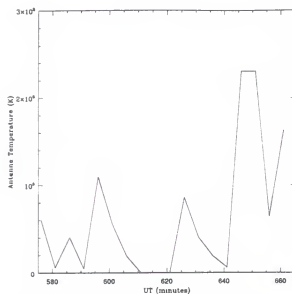


Figure 2.12: The galactic background subtracted antenna temperature of a Jupiter decametric storm. The antenna temperature of the peak for every 5 minute interval is subtracted from the interpolated galactic background over that interval.

CHAPTER 3

RESULTS

3.1 A New Determination of DAM Source Locations in CML and Io Phase

Before proceeding with a study of the effect of D_E changes on the Jovian decametric emission it is enlightening to investigate the average location of the Io- and non-Io-related sources in CML and Io phase space. Table 3.1 provides a consistent and uniformly defined range of CML and Io phase coordinates for all the sources apparent in the range from 18 to 22 MHz. The data used for these definitions are the 18 MHz Yagi data set from 1957-1994, the 20 MHz data set from 1964-1994 and the 22 MHz data set from 1957-1994. The edges of these sources are defined at 10% of the peak value for each source at each frequency. The final values for the source locations were chosen to span the sources at each of the three frequencies mentioned above. Since this data set spans the entire range of D_E as well, it will enclose the source regardless of any shifts in CML or Io phase. This definition of the decametric source boundaries is based on a more extensive data set than is the widely used one reproduced from Carr *et al.* [1983] as Table 1.1

3.2 Occurrence Probability and Average Flux Density

Two methods for specifying the “activity” of a source are considered. One is to make an estimate of the occurrence probability of the Jovian emission over an indicated time period. The other is to estimate the average Jovian flux density (with the galactic background subtracted out) over the indicated time period. Results are presented in this section of a test made to determine which of the two methods of specifying Jovian activity

is the more useful in investigating long-term effects such as the activity variations with respect to D_E .

Table 3.1: Source locations in CML and Io phase taken at the 10% of peak level. These ranges span the sources at 18 through 22 MHz and all values of D_E .

Source Designation	CML Range	Io Phase Range
Io-D	75°—200°	105°—136°
Io-B	75°—200°	60°—105°
non-Io-B	105°—180°	
Io-A	190°—288°	225°—270°
Io-A'	200°—288°	186°—225°
non-Io-A	205°—288°	
Io-C	288°—40°	210°—260°
non-Io-C	288°—350°	

The occurrence probability at the specified frequency is defined as the ratio of the total time during which there was detectable Jovian activity to the total time of effective “listening” for activity. The average flux density at the specified frequency is defined as the time average of the background-subtracted Jovian flux density over the total effective listening time. It should be noted that the average flux density, so defined, is simply the flux-density-weighted occurrence probability; i.e., the emissions of higher flux density carry more weight in computing the weighted occurrence probability than do those of lower flux density.

It was necessary to make approximations to simplify the data reduction process because it was not feasible to measure every Jupiter burst. Instead, the highest value of antenna temperature was read and recorded for each 5-minute interval of listening time. For the results presented in this section, the occurrences probability and average flux density were calculated in turn for 5° bins of CML, 5° bins of Io phase, and 1° bins of D_E . The calculation procedure for each bin is summarized here. For a given bin, let:

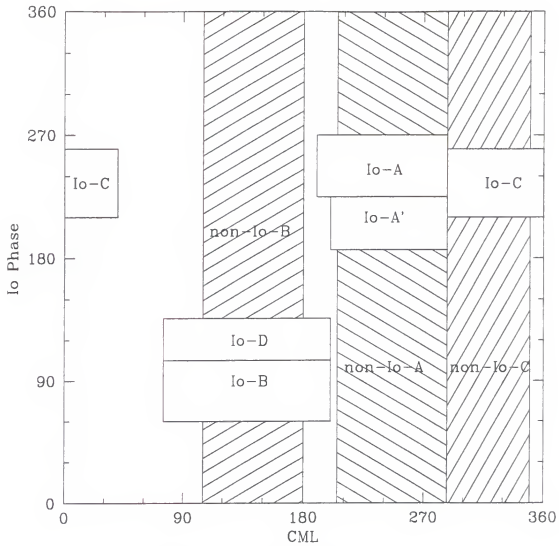


Figure 3.1: An illustration of the source regions defined in Table 3.1

n = the total number of 5 minute intervals of listening time and $1 \leq i \leq n$

$T_{Ji} = T_{Ai} - T_G$, the peak value of Jovian antenna temperature

(adjusted for line loss) for 5-minute interval i ,

where T_{Ai} = total antenna temperature and T_G =
temperature of galactic background

S_i = peak value of Jovian flux density for 5-minute interval i where

$S_i = (2k/A_e)T_{Ji}$ where k = Boltzmann's constant and

A_e = antenna effective area.

$\langle S \rangle = \frac{1}{n} \sum_{i=1}^n S_i$ = average flux density, i.e., the average of the peak values over
all of the 5-minute intervals of listening time.

$T_{\min}$ = standardized value of minimum detectable Jovian antenna
temperature, i.e., the value determined for the apparition of highest
galactic background temperature.

$p_i = 1$ if $T_{Ai} \geq T_{\min}$; $p_i = 0$ if $T_{Ai} < T_{\min}$.

$P = \frac{1}{n} \sum_{i=1}^n p_i$ = occurrence probability

What will be called the occurrence probability in this chapter is actually the galactic background limited occurrence probability as defined in Chapter 2. The occurrence probability and the flux density are of course not entirely independent of one another. The stronger the bursts are the more likely it is that they will be detected. In Section 3.3 however, non-Io-B is shown to be a low flux density but high occurrence probability source. Figure 3.2 shows a plot of occurrence probability and flux density against CML and Io phase for the 1987-1988 apparition at 18 MHz. As expected, there is clearly a strong correlation between the two pairs of curves. For the analyses of long-term variations of Jovian activity to be presented in subsequent sections of this dissertation, a decision had to be made whether to use occurrence probability or average flux density as the measure of activity. The plots in Figures 3.3 and 3.4 were used as a test to determine which of the two quantities would be the more suitable for revealing the sought-for

effects. Figure 3.3 is a plot of occurrence probability as a function of D_E for 1° intervals of the latter, and Figure 3.4 is the same except that average flux density is used instead of occurrence probability. It is clear that the occurrence probability plot indicates a smoother variation with respect to D_E than does the average flux density plot. Average flux density appears to be more subject to random fluctuations. Occurrence probability will therefore be used more often than average flux density as the activity indicator in the plots which follow. The reason for the larger random fluctuations in average flux density is not known. It might be largely due to errors in calibration and in correcting for system losses, or alternatively it might result from an actual randomness in the radiation intensity during periods of activity. In support of this latter idea, an unexplained sudden violent intensity increase is often observed during a noise storm; such events would tend to increase the random fluctuations in average flux density.

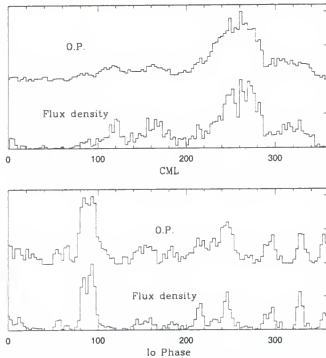


Figure 3.2: Comparison of occurrence probability and flux density against central meridian longitude and Io phase at 18 MHz during the 1987-88 apparition.

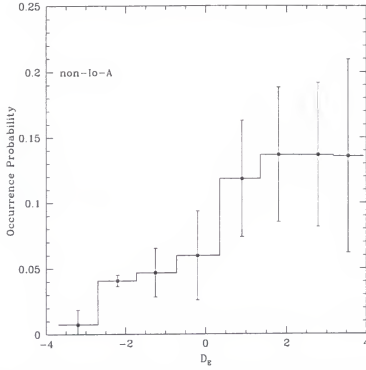


Figure 3.3: The D_E dependence of the non-Io-A occurrence probability at 18 MHz. The occurrence probability for apparitions from 1957-1994 are in 1 degree bins of D_E .

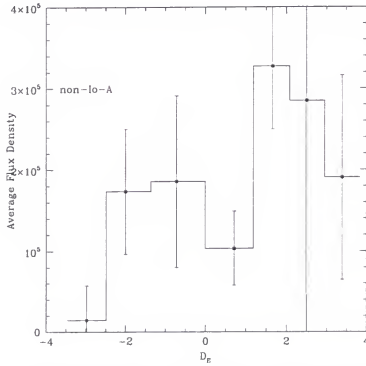


Figure 3.4: A histogram illustrating the D_E dependence of the non-Io-A flux density at 18 MHz. The average flux density for apparitions from 1965-1993 are in 1 degree bins of D_E . The definition of average flux density is given in the text.

3.2.1 Source Widths and Locations

In order to investigate the variation in source location and width over the range of D_E and to improve the statistical confidence, the apparitions were grouped by their seasonal averaged D_E value. Table 3.2 lists the apparitions that were combined to form each D_E group. Figure 3.5 illustrates the changes in occurrence probability for all of the Io-related and non-Io-related sources with frequency and D_E . All the sources appear to be influenced by D_E at each frequency and most of this chapter is devoted to studying to what extent the source characteristics are influenced by changes in D_E .

Table 3.2: The division of apparitions into groups of similar D_E values. The table gives the D_E ranges and the apparitions which are combined for each of these sets.

D_E range	18 MHz	20 MHz	22 MHz
< -2.5	57-58, 58-59, 69-70, 70-71, 81-82, 83, 92-93, 94	69-70, 70-71, 81-82, 83, 92-93, 94	same as 18 MHz
$-2.5 < D_E < -1.0$	59-60, 68-69, 72, 79-80, 80-81, 84, 91-92	68-69, 72, 79-80, 80-81, 84, 91-92	
$-1.0 < D_E < 1.0$	61-62, 67-68, 73, 78-79, 85, 90-91	67-68, 73, 78-79, 85, 90-91	
$1.0 < D_E < 2.5$	62-63, 65, 66, 74, 77-78, 86, 89-90	65, 66, 77-78, 86, 89-90	
> 2.5	63-64, 64-65, 75-76, 76-77, 87-88, 88-89	64-65, 75-76, 76-77, 87-88, 88-89	

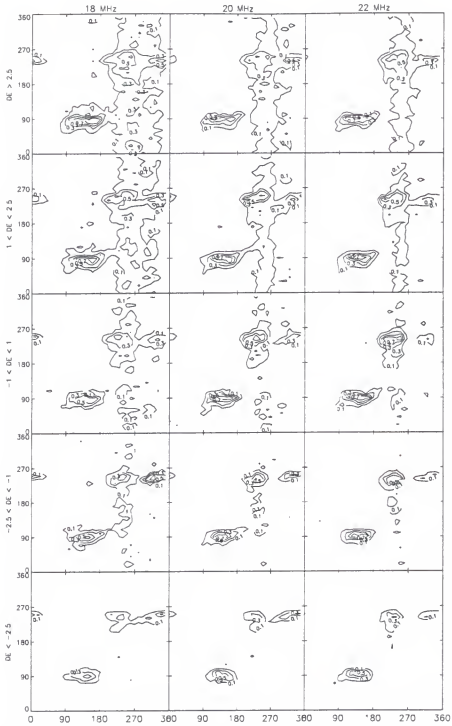


Figure 3.5: Contours of constant occurrence probability in the Io phase (vertical axis) versus CML (horizontal axis) plane. This plane is represented for each of 3 frequencies (columns) and 5 D_E ranges (rows). The D_E groups are the same as those listed in Table 3.2

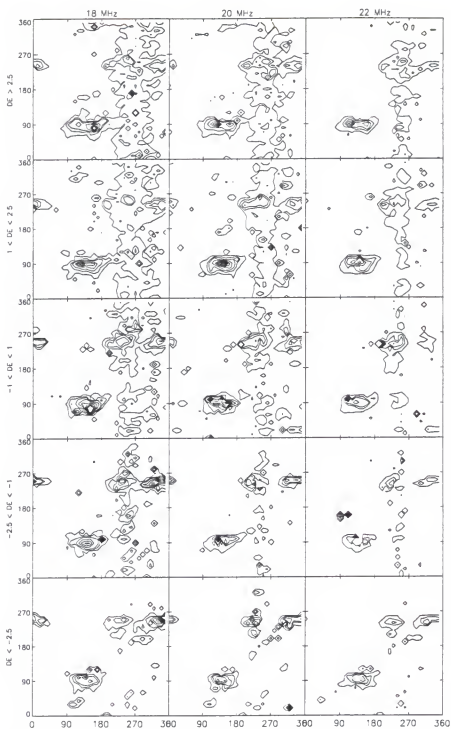


Figure 3.6: Same as Figure 3.5 but now the contours for each represent average flux density. The D_E groups are the same as in Table 3.2 except excluding seasons before 1965.

Four points have been used to describe the source width and shape in the CML and Io phase histograms. The first point is the location of the peak of the source. The height

of the peak is used to determine the two full-width half maximum points, called the high edge and low edge. The width of the source is the difference between these two points. For the non-Io-A source and all of the other sources studied in this report the data at 18 MHz have been used exclusively to determine source width and locations. The reason for this choice is that there is more activity recorded at 18 MHz than at 20 or 22 MHz. Merging the data from the three frequencies would not be useful since the location of the sources are frequency dependent as can be seen in Figure 1.1. The CML and Io phase histograms were originally in 3° bins but in order to improve our ability to identify the peaks and half maximum points the data was smoothed and rebinned to 1.5° .

3.3 Verification of the Low Intensity High Probability Non-Io-B Source

The 26.3 MHz antenna is a filled array composed of 640 dipoles, each dipole oriented in the east-west direction. There are 16 dipoles in the east-west direction and 40 in the north-south direction. The bandwidth of the array is about 1 MHz, but for Jupiter observations it is usually used with a receiver having a bandwidth of 0.25 MHz. The latter value is the overall system bandwidth. The sensitivity limit of the array is about 100 Janskys compared to 60,000 Janskys for the Yagi antenna system at the same frequency [Desch *et al.*, 1975]. For this study, the 26.3 MHz array data format, referred to as the raw data card in Thieman's dissertation [Thieman, 1977], was converted into one similar to the format used for the Yagi data as shown in Figure 2.1. All of the data for each apparition were used without regard to the storm characteristics or credibility tags given in the raw data file. A thorough discussion of the instrumentation and data reduction method of the 26 MHz array data is given in Desch's dissertation [Desch, 1976].

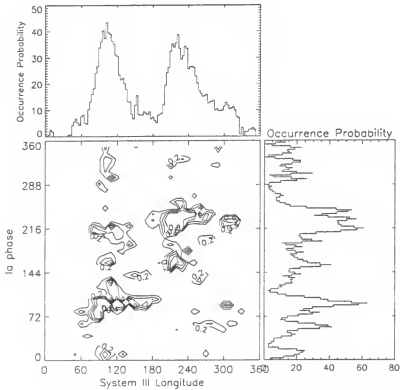
The dramatic increase in sensitivity of this instrument makes possible the study of relatively weak components of the Jovian decametric radiation. From the data obtained

during the first apparition in which the large array was used for Jupiter observations (the 1973 apparition), Desch *et al.* [1975] discovered a high probability non- Io-B component that had not previously been recognized because of the low peak flux densities of its bursts. These flux densities were found to be considerably less than those for the bursts of Io-B , Io-A , Io-C and non- Io-A . However, there has yet been no confirmation of the Desch *et al.* paper. This section is a report on a complete confirmation of the Desch *et al.* finding, based on the large 26.3 MHz array data obtained during the 7 apparitions following that of the Desch *et al.* paper. Table 3.3 summarizes the large array data used.

It should be noted that the Yagi-obtained data in Figures 3.5 and 3.6 indicate for the high- D_E CML-Io phase plots a very low probability and low flux density for the non- Io-B region at 18 MHz. There is essentially no activity for the corresponding low- D_E groups. At the higher frequencies, there is virtually no detectable non- Io-B activity. Figures 3.7 to 3.15 for the large-array data, on the other hand, show relatively high occurrence probabilities for the non- Io-B data. Figures 3.7 through 3.14 show for each of the apparitions a plot of contours of constant occurrence probability on the CML-Io phase plane, together with histograms of occurrence probability vs. CML and occurrence probability vs., Io phase. Figure 3.15 contains similar plots for the aggregate of all the data, together with the corresponding Yagi-obtained plots for comparison. This latter figure best indicates that the conclusions of Desch *et al.* [1975] were valid.

Table 3.3: An overview of the 26.3 MHz array data used in this study.

Season	Begin Date	End Date	Listening (hours)	Activity (hours)	Occurrence Probability
1973	4-16-73	12-30-73	529.333	82.583	0.156
1974-75	1-23-74	2-28-75	476.583	81.167	0.170
1975-76	6-28-75	4-27-76	484.667	81.917	0.169
1976-77	9-27-76	5-19-77	435.167	59.000	0.136
1977-78	10-24-77	5-4-78	214.167	48.583	0.227
1978-79	11-13-78	4-10-79	339.250	42.917	0.126
1979-80	11-21-79	4-10-80	281.750	24.417	0.087
1981	1-5-81	4-28-81	236.500	18.583	0.078

Figure 3.7: 26.3 MHz Array, 1973 apparition. This plot is of the same data used in Desch *et al.*, 1975.

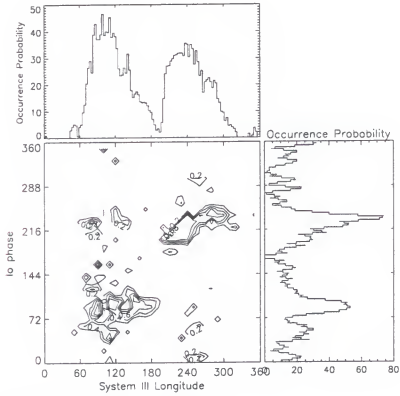


Figure 3.8: 26.3 MHz Array, 1974-75 apparition.

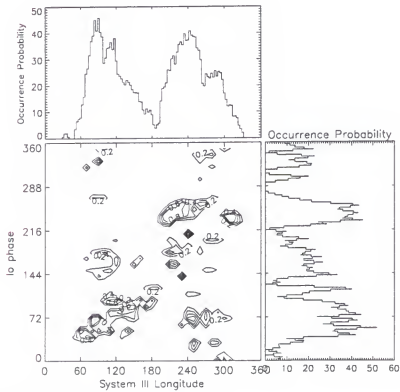


Figure 3.9: 26.3 MHz Array, 1975-76 apparition.

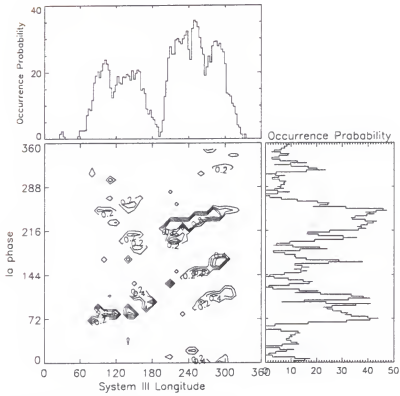


Figure 3.10: 26.3 MHz Array, 1976-77 apparition.

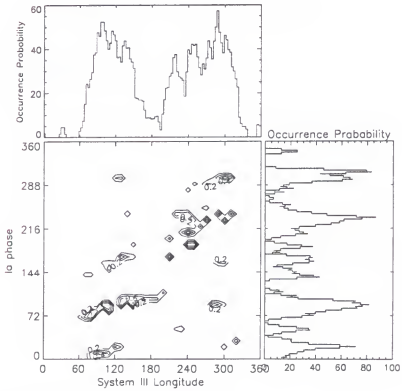


Figure 3.11: 26.3 MHz Array, 1977-78 apparition.

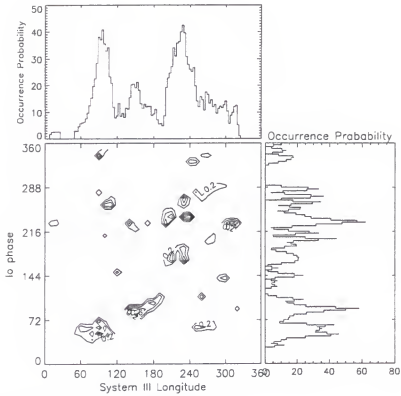


Figure 3.12: 26.3 MHz Array, 1978-79 apparition.

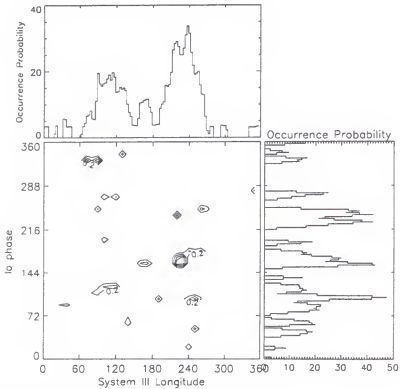


Figure 3.13: 26.3 MHz Array, 1979-80 apparition.

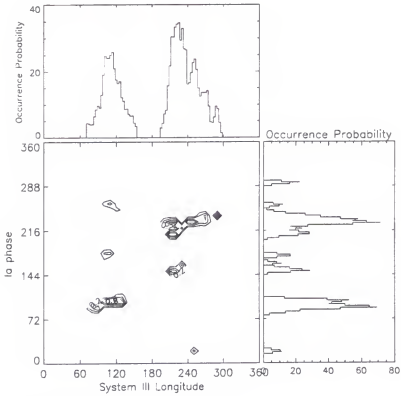


Figure 3.14: 26.3 MHz Array, 1981 apparition.

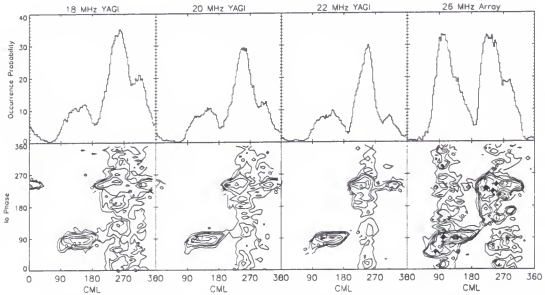


Figure 3.15: A comparison of occurrence probabilities between 18, 20 and 22 MHz Yagi antennas and the 26.3 MHz array for the integrated apparitions from 1973 to 1981. The top row are CML histograms of occurrence probability and the bottom row are CML-Io phase contour plots. The contours are at occurrence probabilities of 10, 20, 40, 60 and 80%.

3.4 The D_E Effect on the Non-Io-A Source

Of all the sources shown in the CML-Io phase contour plots of Figure 3.5 it is the non-Io-related A source which suffers the most dramatic changes with D_E . Figure 3.19 shows that the changes in source width and location for non-Io-A are very large over the roughly 7 degree range of D_E . The high CML edge of the non-Io-A source has a very strong dependence on D_E . The occurrence probability of the non-Io-A source varies in close step with D_E as seen in Figure 3.20. Figure 3.16 through 3.18 show the data and best fit lines of the different sections of non-Io-A. The lines in these figures represent the best fits to the source using data from every apparition in which these locations could accurately be determined. These best fit lines are reproduced in summary in Figure 3.19.

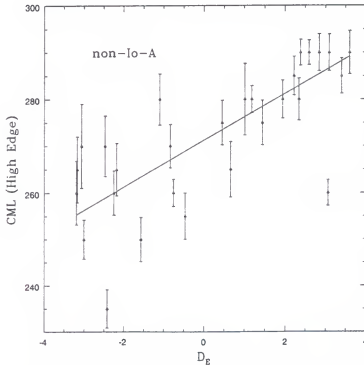


Figure 3.16: The high CML edge of the non-Io-A source at 18 MHz for each apparition. The high and low CML edges are defined by the full-width-half maximum longitude of the occurrence probability. The error bars are proportional to the inverse square root of the amount of listening time for the non-Io-A source during each apparition.

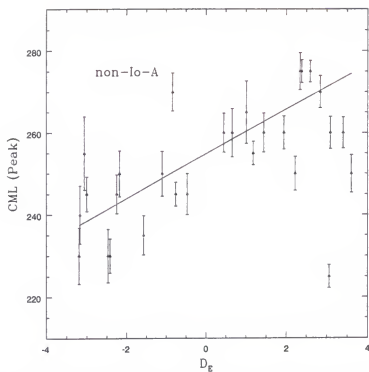


Figure 3.17: The CML of the peak of the non-Io-A source at 18 MHz for each apparition.

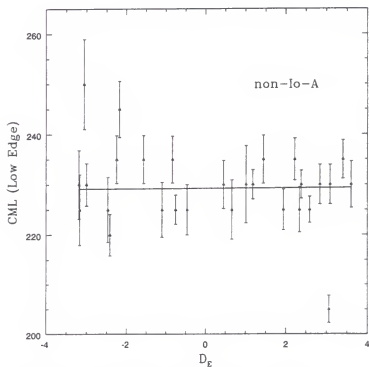


Figure 3.18: The low CML edge of the non-Io-A source at 18 MHz.

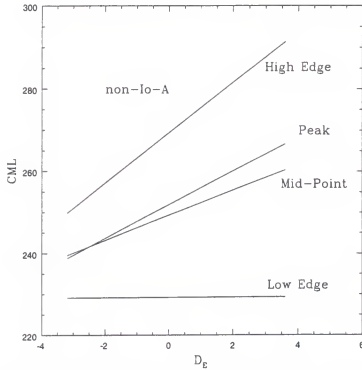


Figure 3.19: The best fit lines to the non-Io-A CML peak, midpoint and edges. The lines are the same as those in Figures 3.16–3.18. The values for the slopes and the errors in the slopes of these lines are presented in Table 3.5

The degree to which the shape of each of the sources and the occurrence probability depends on D_E is tested using Spearman's rank correlation coefficient [Press *et al.*, 1992]. A statistical test is performed to see whether the data allow for the rejection of the null hypothesis of no D_E dependence in favor of the alternative that there is some degree of D_E dependence in the data. Spearman's rank correlation coefficient is described in more detail in Appendix B. Table 3.4 lists each of the characteristics of non-Io-A that have been tested for the D_E effect and the likelihood of a D_E dependence. The three columns labeled Very Likely, Possible and Inconclusive expresses the degree of confidence in the rejection of the null hypothesis of no D_E effect. We perform a Student's t test of the probability of obtaining a nonzero correlation coefficient when the true correlation is zero. A D_E dependence that is *very likely* is chosen when we can be 95% confident that the null hypothesis can be rejected in favor of the alternative of some D_E dependence.

A possible D_E dependence is one where we can be 80-95% confident of rejecting the null hypothesis. A D_E dependence that is *inconclusive* is one where we cannot reject the null hypothesis at even the 80% confidence interval. The first column is r_s , Spearman's rank correlation coefficient, the second column is $d.f.$, the degrees of freedom. Table 3.5 gives the slopes of those lines which had a very likely correlation with D_E . The best fit line to the longitude of the non-Io-A peak was computed twice and the slope is given for both fits in Table 3.5. The second fit excluded data with D_E greater than about 3° . The reason for this is that there is evidence presented later in this section that the non-Io-A source has a different dependence on D_E at the high end of the range.

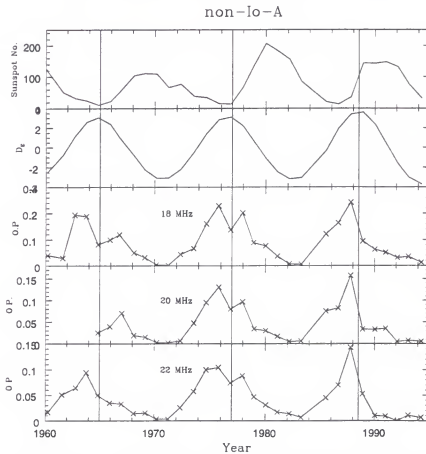


Figure 3.20: Plots of seasonal averaged sunspot number, D_E and occurrence probability at 18, 20 and 22 MHz for non-Io-A. The vertical lines mark the dates of highest D_E .

Table 3.4: Confidence of D_E dependence on non- I_o -A source characteristics. The first column is Spearman's rank correlation coefficient, the second column is the degrees of freedom.

D_E Dependence					
non- I_o -A	r_s	d.f.	Very Likely $\geq 95\%$	Possible 80-95%	Inconclusive $< 80\%$
Probability @ 18 MHz	.87	31	X		
Probability @ 20 MHz	.80	25	X		
Probability @ 22 MHz	.76	31	X		
CML of Peak	.51	26	X		
High CML Edge	.69	26	X		
Low CML Edge	-.27	26		X	

Table 3.5: The slopes and errors for those non- I_o -A source characteristics demonstrating a very likely dependence on D_E .

D_E Dependence			
non- I_o -A	1 degree binned data	Slope	Standard Deviation
	Probability @ 18 MHz	0.0209	0.0056
	CML of Peak	2.13	3.88
	CML of Peak without notch	5.45	0.71
	High CML Edge	4.15	1.94

3.5 The D_E Effect on the Other DAM Sources

3.5.1 Io-B

A CML-Io phase plot of Io-B reveals a complicated structure. A typical Io-B contour plot is that of the 1965-66 apparition shown in Figures 3.21–3.23. Nearly all apparitions show a relatively sharp cutoff of the Io-B source at high Io phase and a more gradual drop toward lower Io phase. The features labeled *I* and *II* appear as a bifurcation of source Io-B in the CML and Io phase coordinates. Both of these features were noted by Leacock and Smith [1973], Thieman, Smith and May [1975] and Thieman and Smith [1978]. The bifurcation in CML was noted by Gallet [1961], Smith, Carr and Six [1962] and Barrow [1981]. No physical explanation has been presented to explain the splitting of the Io-B source but it is a recurrent feature confirmed by our data. Feature *III* is a bridge of enhanced occurrence probability apparently connecting the Io-B source to the non-Io-A source. Feature *IV* is the Io-D source which appears weakly at 18 MHz and high D_E but is virtually nonexistent in the 20 and 22 MHz data. Figure 3.23 is a close-up of Figure 3.21 now showing only the Io-B source. These plots are integrated over several apparitions and therefore some of the finer details have been smoothed. The contours in Figure 3.22 represent the average flux density. The overall shapes match quite closely the occurrence probability plots of Figure 3.21 but the relative importance of the central peaks of the Io-B source is greater and the CML histogram shows more clearly the bifurcation of the Io-B source. The flux density histograms have not been smoothed.

Similar to the A source, there is also an associated non-Io related component to the B source. Non-Io-B is very weak compared to the other DAM sources. No attempt was made to study the D_E dependence of this source but for completeness the mean values for the peak, low and high edges of the source are shown in Figure 3.39.

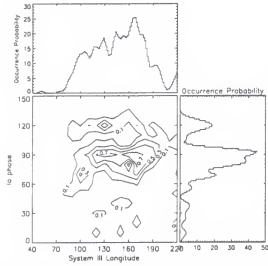


Figure 3.21: A CML-Io phase occurrence probability contour plot of Io-B for the 1965-66 apparition at 18 MHz. The histograms in CML and Io phase can be interpreted as projections of the contour plot along the two coordinates.

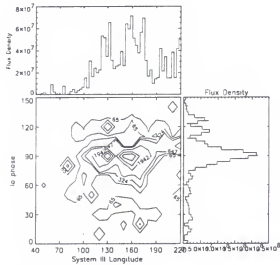


Figure 3.22: Same as Figure 3.21 but now contours represent average flux density. The histograms are the sum of the flux density received within each bin. Units are in Janskys ($10^{-26} \text{ W} / \text{m}^2 \text{ Hz}$)

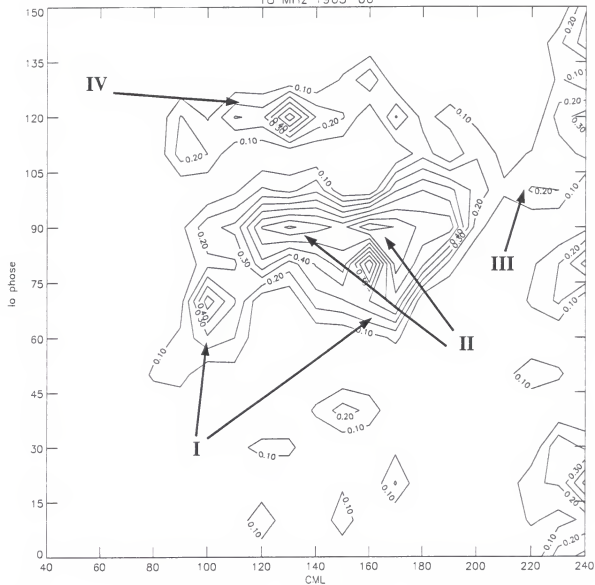


Figure 3.23: An enlargement of the contour plot of Figure 3.21 illustrating recurrent features of the source.

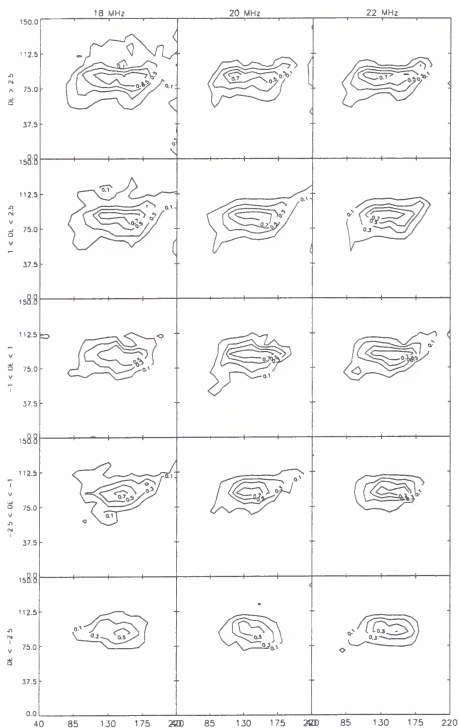


Figure 3.24: Contours of constant occurrence probability in the Io phase (vertical axis) versus CML (horizontal axis) plane. The region containing the Io-B source is represented for each of 3 frequencies (columns) and 5 De ranges (rows). The De groups are the same as those listed in Table 3.2

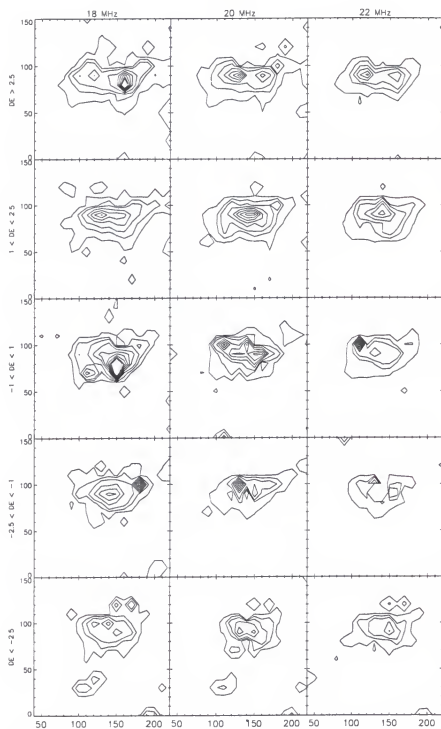


Figure 3.25: Same as Figure 3.24 but now for contours of average flux density. The D_E groups are the same as in Table 3.2 except excluding seasons before 1965.

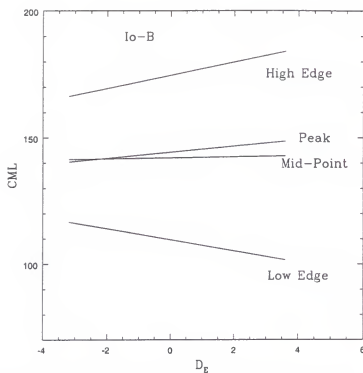


Figure 3.26: The best fit lines to the Io-B CML peak, midpoint and edges.

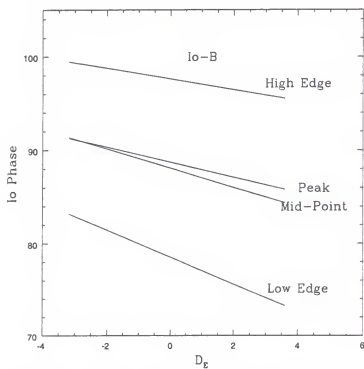


Figure 3.27: The best fit lines to the Io-B Io phase peak, midpoint and edges.

Table 3.6 lists a D_E dependence for both the low and high CML edges of the Io-B source. Figure 3.26 shows that the low CML edge tends towards lower longitudes with increasing D_E . The D_E dependence of the CML of the peak point is not as certain as are the low and high edges. The midpoint is computed from the low and high edges and its small slope reflects the opposite slopes of the two edges. Figure 3.27 shows the source drifts toward lower Io phase with increasing D_E . The slightly higher slope of the low edge might be due to the apparent growth of feature *I* with D_E as seen in Figure 3.24. Figure 3.28 compares the time series of the seasonal averaged sunspot number, D_E and occurrence probability for Io-B at 18, 20 and 22 MHz. The vertical lines aid the eye in matching features in the curves to the dates of maximum D_E . The rise in D_E appears to be matched with a rise in occurrence probability except for a drop in probability at the maximum D_E values. The seasonal averaged sunspot number in Figure 3.28 is computed from the monthly R number obtained from the National Solar Observatory/Sacramento Peak. Only those months which span the observing season are used to compute the average.

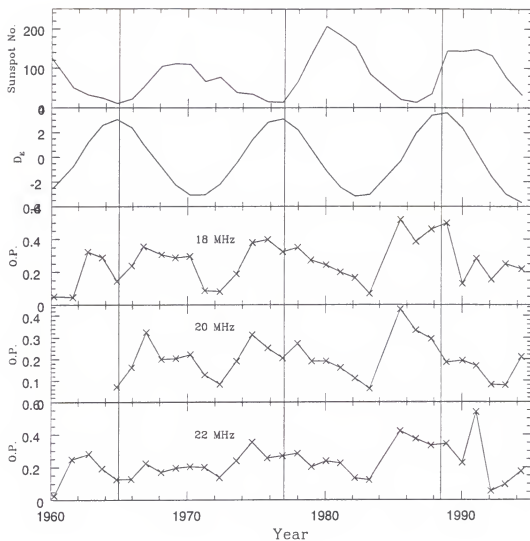


Figure 3.28: Plots of seasonal averaged sunspot number, D_E and occurrence probability at 18, 20 and 22 MHz for Io-B. The vertical lines mark the dates of highest D_E .

Table 3.6: Confidence of D_E dependence on Io-B and non-Io-B source characteristics

D_E Dependence					
Io-B	r_s	d.f.	Very Likely $\geq 95\%$	Possible 80-95%	Inconclusive <80%
Probability @ 18 MHz	.59	31	X		
Probability @ 20 MHz	.33	25		X	
Probability @ 22 MHz	.55	31	X		
CML of Peak	.26	27		X	
Io Phase of Peak	-.56	26	X		
High CML Edge	.68	27	X		
Low CML Edge	-.40	27	X		
High Io Phase Edge	-.88	21	X		
Low Io Phase Edge	-.62	21	X		

Table 3.7: The slopes and errors of those characteristics of the Io-B source demonstrating a very likely D_E dependence

D_E Dependence			
Io-B	1 degree binned data	Slope	Standard Deviation
	Probability @ 18 MHz	0.048	0.023
	Io Phase of Peak	-1.3	1.2
	High CML Edge	2.6	1.2
	Low CML Edge	-2.5	1.2
	High Io Phase Edge	-1.1	0.6
	Low Io Phase Edge	-1.8	1.2

3.5.2 Io-A and Io-A'

The Io-A source on a CML-Io phase diagram shows some similarity with the Io-B source. Both sources tend to have a steep high Io phase edge. Comparing Figures 3.24 and 3.29, both sources appear to become less asymmetric, more rounded with lower D_E . Io-A often appears to have secondary peaks at lower Io phase. These peaks at times are of such high occurrence probability to be nearly equal to the main Io-A peak in detection likelihood. Included among these secondary peaks may be Io-A' itself. It may be that the Io-A' region is simply an extension of Io-A. The Io-A' region is ill-defined, with several peaks all of which are of nearly equal occurrence probability. As D_E increases the non-Io-A component becomes stronger and isolating a single peak as the main Io-A' peak becomes increasingly difficult. Figure 3.31 shows Io-A, Io-A' and non-Io-A in Io phase. This figure illustrates the difficulty in identifying permanent Io-A' landmarks and studying trends at least in the Io phase component. From Table 3.1, peaks outside of the range from about 180 to 270 degrees are designated the non-Io-A emission. A drift in Io phase of the Io-A source with D_E is not clear in this data. Only the high Io phase edge seems to indicate a definite dependence with D_E . From Table 3.8, the low Io phase edge shows a possible dependence and the peak shows no dependence on D_E . The CML dependence on D_E for the Io-A source appears to be quite strong. Figure 3.33 shows that the high CML edge of Io-A can vary by over 30 degrees over the 7 degree span of D_E . The occurrence probability of Io-A is also clearly dependent on D_E as seen in Figure 3.34. The occurrence probabilities tend to rise with higher D_E but there is evidence of a drop at the maximum D_E values.

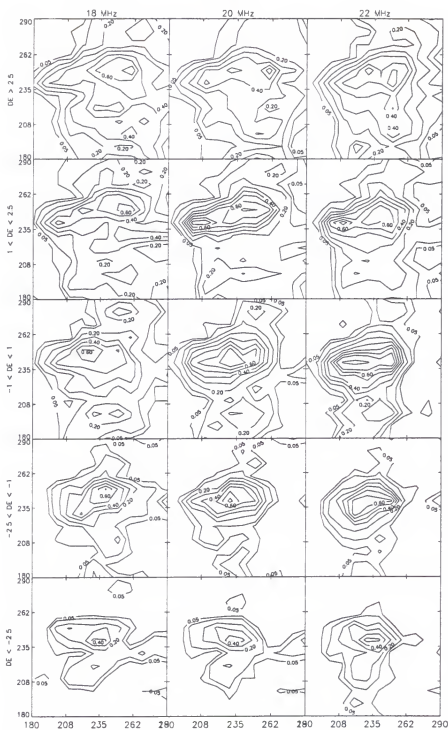


Figure 3.29: Contours of constant occurrence probability in the Io phase (vertical axis) versus CML (horizontal axis) plane. The region containing the Io-A, Io-A' source is represented for each of 3 frequencies (columns) and 5 D_E ranges (rows). The D_E groups are the same as those listed in Table 3.2

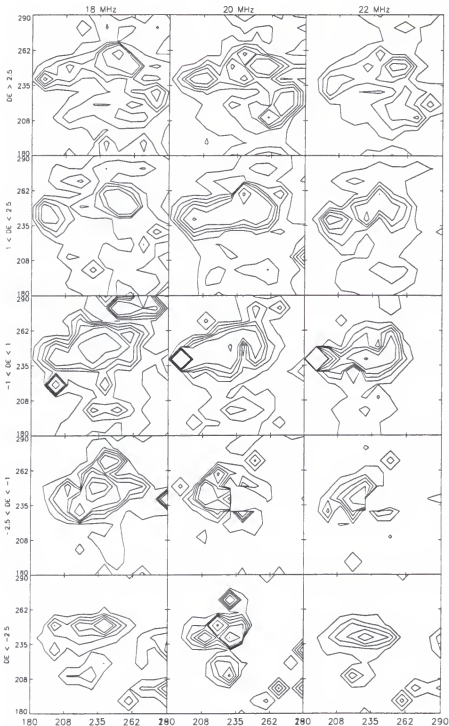


Figure 3.30: Same as Figure 3.29 but now for contours of average flux density. The D_E groups are the same as in Table 3.2 except excluding seasons before 1965.

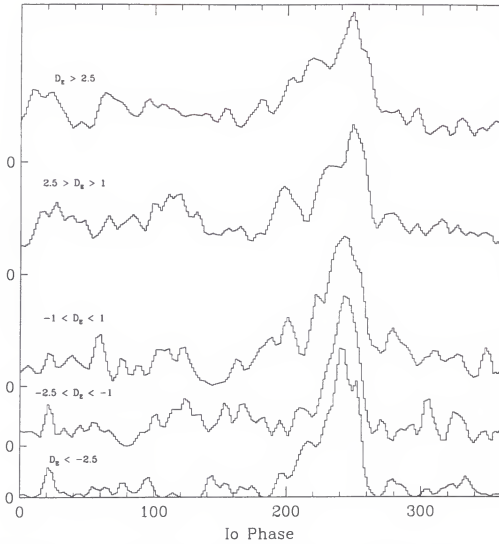


Figure 3.31: Plots of occurrence probability versus Io phase at 18 MHz for various ranges of D_E . These plots are integrated over CML from 200 to 290 degrees. The Io-A peak is at 240 degrees Io phase and the Io-A' peak is between 200 and 220 degrees.

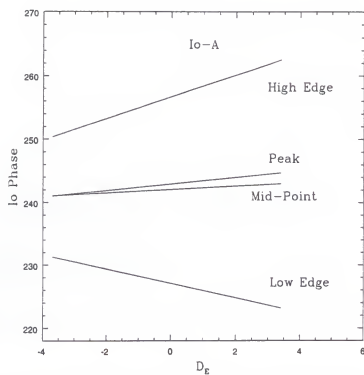


Figure 3.32: The best fit lines to the Io-A Io phase peak, midpoint and edges.

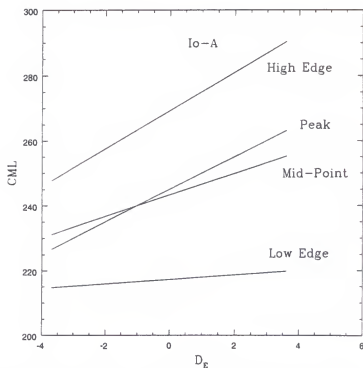


Figure 3.33: The best fit lines to the Io-A CML peak, midpoint and edges.

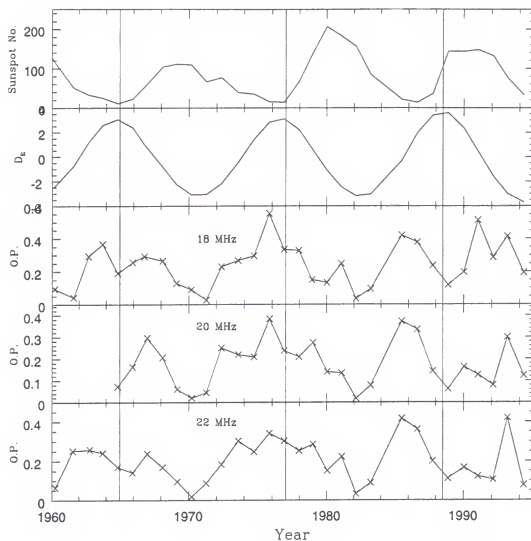


Figure 3.34: Plots of seasonal averaged sunspot number, D_E and occurrence probability at 18, 20 and 22 MHz for Io-A. The vertical lines mark the dates of highest D_E .

Table 3.8: Confidence of D_E dependence on Io-A source characteristics

D_E Dependence					
Io-A	r_s	d.f.	Very Likely $\geq 95\%$	Possible 80-95%	Inconclusive <80%
Probability @ 18 MHz	.46	31	X		
Probability @ 20 MHz	.38	25	X		
Probability @ 22 MHz	.52	31	X		
CML of Peak	.77	26	X		
Io Phase of Peak	-.14	17			X
High CML Edge	.86	26	X		
Low CML Edge	.29	26		X	
High Io Phase Edge	.58	17	X		
Low Io Phase Edge	-.36	17		X	

Table 3.9: The slopes and errors of Io-A source characteristics demonstrating a very likely D_E dependence.

D_E Dependence			
Io-A	1 degree binned data	Slope	Standard Deviation
	Probability @ 18 MHz	.02	.04
	CML of Peak	4.5	1.7
	High CML Edge	5.7	2.6
	High Io Phase Edge	1.2	1.4

Table 3.10: Confidence of D_E dependence on Io-A' source characteristics

D_E Dependence					
Io-A'	r_s	d.f.	Very Likely $\geq 95\%$	Possible 80-95%	Inconclusive <80%
Probability @ 18 MHz	.79	31	X		
Probability @ 20 MHz	.75	25	X		
Probability @ 22 MHz	.68	31	X		
CML of Peak	.58	21	X		
High CML Edge	.81	21	X		
Low CML Edge	.14	21			X

Table 3.11: The slopes and errors of Io-A source characteristics demonstrating a very likely D_E dependence.

D_E Dependence			
Io-A'	1 degree binned data	Slope	Standard Deviation
	Probability @ 18 MHz	.03	.01
	CML of Peak	3.4	3.7
	High CML Edge	6.6	1.8

3.5.3 Io-C and Non-Io-C

The Io-C source seems to exhibit little change in position, shape and occurrence probability with D_E . It does seem to show a strong frequency dependence, however. Figure 3.35 illustrates the large differences in the Io-C source with frequency and the mild dependence with D_E . Figure 3.36 also illustrates that the D_E dependence in CML is weak. Figure 3.37 on the other hand indicates a clear D_E dependence in Io phase. The occurrence probability plots of Figure 3.38 do not appear to show any correlations but a test of the Spearman's rank correlation coefficient indicates that at least at 18 and 22 MHz there is sufficient confidence in the correlation to reject the null hypothesis. Apparently at 20 MHz due to a poorer correlation and insufficient data it is not possible to make any conclusions on the correlation of the occurrence probability with D_E .

The non-Io-C source typically had an occurrence probability about half that of the non-Io-A source. The occurrence probability had a correlation coefficient sufficiently high according to the criteria set earlier in this chapter to have a very likely dependence on D_E . The slope of occurrence probability versus D_E was found for this source and is reported in Table 3.13. Because non-Io-C was relatively weak, a study of the correlation of the peaks and edges of the source was not performed. The mean location of the non-Io-C peak and edges are shown in Figure 3.39.

The results of Thieman and Smith [1978] from observations of Io-C at 10 to 30 MHz shows a drift in the peak of the source towards higher longitude with lower frequency. This result is confirmed in recent data obtained by the Wind spacecraft [Kaiser and Garcia, 1996]. These results show that between the frequencies of 2 and 14 MHz the Io-C source is shifted by about 40-50° relative to its location in the frequency range of 18 to 22 MHz.

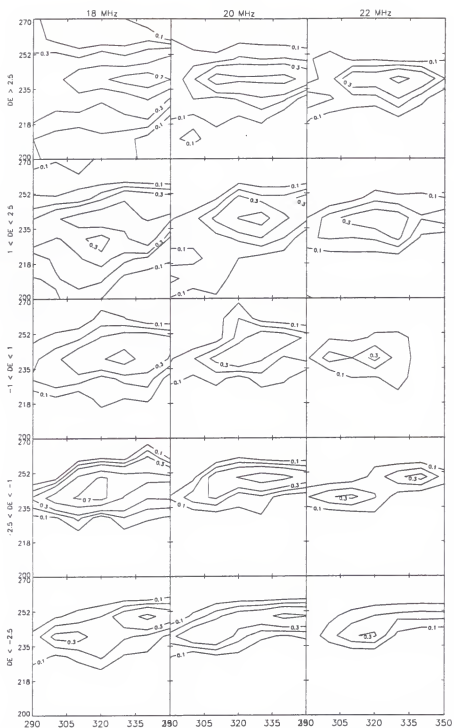


Figure 3.35: Contours of constant occurrence probability in the Io phase (vertical axis) versus CML (horizontal axis) plane. The region containing the Io-C source is represented for each of 3 frequencies (columns) and 5 DE ranges (rows). The DE groups are the same as those listed in Table 3.2

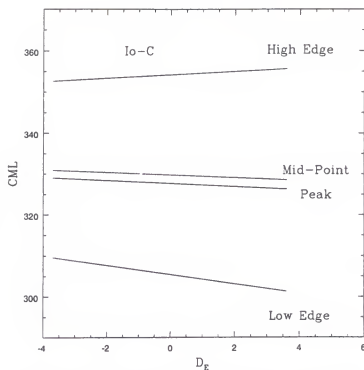


Figure 3.36: The best fit lines to the Io-C CML peak, midpoint and edges.

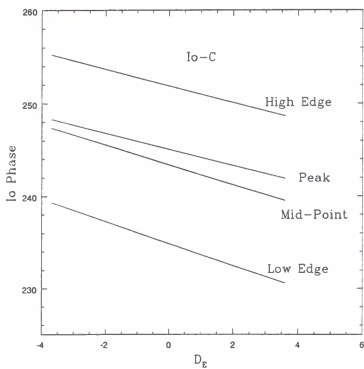


Figure 3.37: The best fit lines to the Io-C Io phase peak, midpoint and edges.

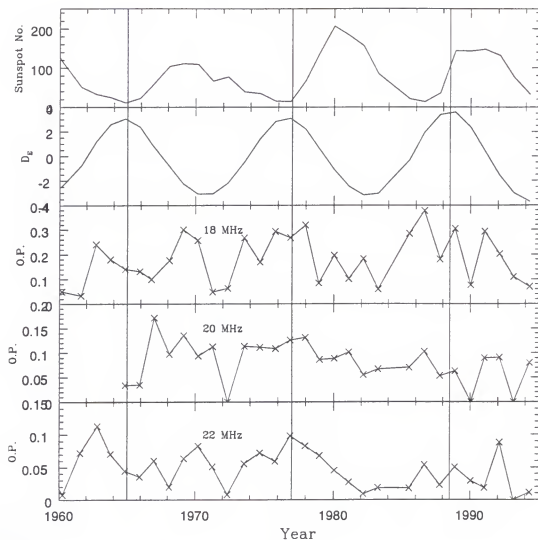


Figure 3.38: Plots of seasonal averaged sunspot number, D_E and occurrence probability at 18, 20 and 22 MHz for Io-C. The vertical lines mark the dates of highest D_E .

Table 3.12: Confidence of D_E dependence on Io-C source characteristics

D_E Dependence					
Io-C	r_s	d.f.	Very Likely $\geq 95\%$	Possible 80-95%	Inconclusive $< 80\%$
Probability @ 18 MHz	.47	31	X		
Probability @ 20 MHz	-.01	25			X
Probability @ 22 MHz	.38	31	X		
CML of Peak	-.08	25			X
Io Phase of Peak	-.87	21	X		
High CML Edge	.12	25			X
Low CML Edge	-.25	25			X
High Io Phase Edge	-.88	21	X		
Low Io Phase Edge	-.62	21	X		
non-Io-C					
Probability @ 18 MHz	.82	31	X		

Table 3.13: The slopes and errors of those characteristics of the Io-C source demonstrating a very likely D_E dependence

D_E Dependence			
Io-C	1 degree binned data	Slope	Standard Deviation
	Probability @ 18 MHz	0.024	0.021
	Io Phase of Peak	-0.94	0.63
	High Io Phase Edge	-0.84	0.42
	Low Io Phase Edge	-1.4	0.9
non-Io-C	Probability @ 18 MHz	.0079	.0065

3.5.4 Summary

The D_E dependence of the shapes of the sources described in this chapter is summarized in Figure 3.39 and Figure 3.40. The lines are for the low CML, high CML and peak locations of each source as defined previously. Solid lines represent those features of the source which are very likely to have a D_E dependence. The dashed lines are for those features which could not be proven to have any D_E dependence. The dashed lines replace the best fit lines and are drawn at the mean value of the edge or peak of the source.

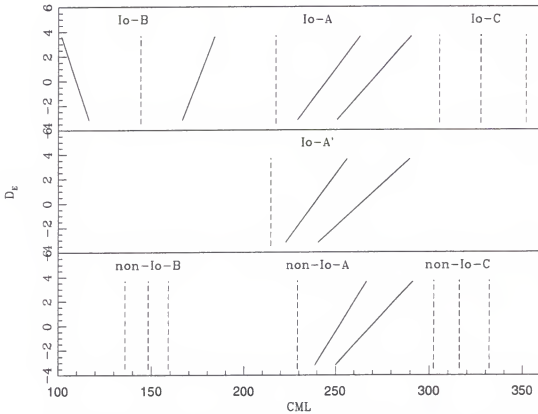


Figure 3.39: The best fit lines to the low, high and peak CML locations for each of the sources discussed in this chapter. The vertical dashed lines represent peaks or edges which could not be proven to have a D_E dependence.

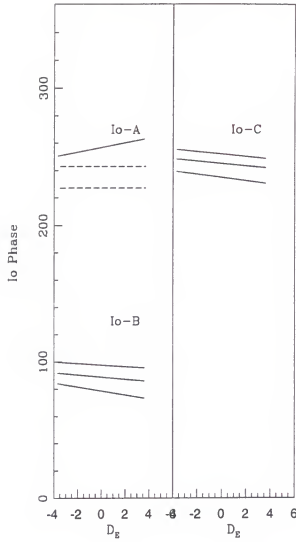


Figure 3.40: The best fit lines to the low, high and peak Io phase locations for most of the sources discussed in this chapter. The horizontal dashed lines represent peaks or edges which could not be proven to have a D_E dependence.

3.6 Models of the Non-Io-A Occurrence Probability versus Time

3.6.1 Model 1: Based on Assumed Variation of OP with D_E

Based on the accumulated evidence presented in this chapter we began to model the long-term variations of the non-Io-A source under the assumption of a direct, linear relationship with D_E . This relationship can be expressed in the formula

$$OP = A \cdot P_{D_E} \quad (3-1)$$

where A is the constant of proportionality which minimizes the sum of squared residuals of the data to the model. P_{D_E} is given by

$$P_{D_E} = \frac{1}{7.6}(D_E + 4) \quad (3-2)$$

expressing the D_E dependence of the occurrence probability and has a maximum value of 1. Figure 3.41 is a plot of the occurrence probability at 18 MHz for the non-Io-A source. The data have been divided into three sections based on the dates of minimum D_E . P_{D_E} for sections 1, 2 and 3 is shown in Figure 3.42. Figure 3.43 shows the model fit based on Equation 3.1 and Figure 3.42. The model does well at matching the locations of the peaks in sections 1 and 2 but fails to reach the minimum occurrence probabilities around 1970 and 1982. In sections 1 and 2 there is a clear “notch” at the occurrence probability peak which is not accounted for in the model. The model does not match the asymmetry of the occurrence probabilities peaks around the “notch” and fails to drop sufficiently to match section 3 well.

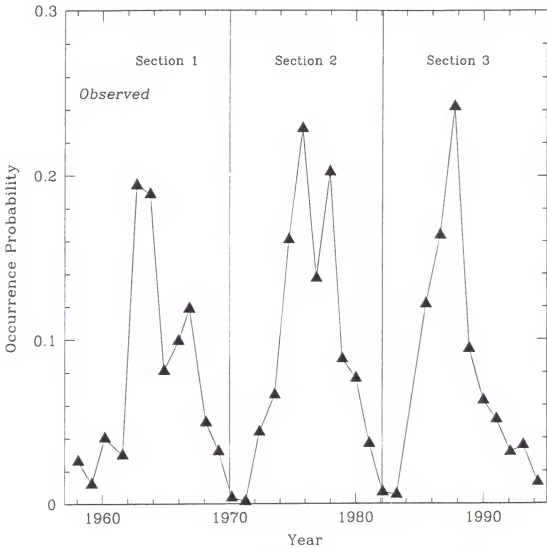


Figure 3.41: The non-Io-A occurrence probability values from 1957 through 1994 at 18 MHz. The three sections are divided by dates of minimum D_E value.

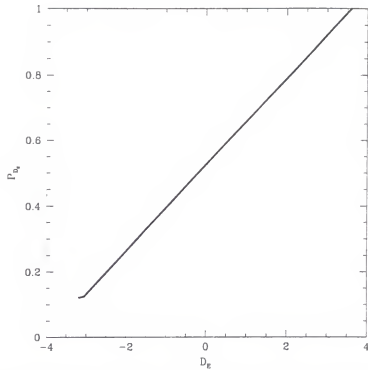


Figure 3.42: P_{DE} for sections 1, 2 and 3. P_{DE} is the probability factor which expresses the D_E dependence of the occurrence probability.

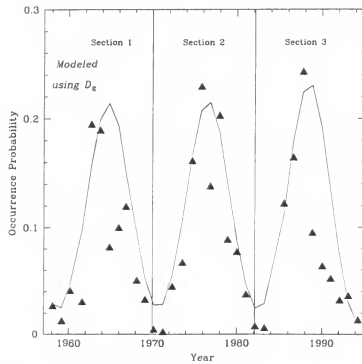


Figure 3.43: Model 1 of the occurrence probability for the 18 MHz non-Io-A source. The constant of proportionality is equal to 0.23 for all three sections. The triangles indicate the observed points.

3.6.2 Model 2a: OP Varies with both D_E and Sunspot Number

It can be seen from Figure 3.44 that throughout nearly the entire data set the seasonal averaged sunspot number was in very close to anti-phase with D_E . Only in the last few years has the sunspot cycle drifted so that the two curves are almost 90° out of phase. It was in this most recent D_E cycle that the occurrence probability dropped sharply, well before D_E had begun to drop. This drop is apparent at all three frequencies studied and is visible in some of the other sources but none as clear as non-Io-A. We are proposing that this steep drop in occurrence probability and the rise in average sunspot number occurring at the about the same time is not coincidental. The model developed as Model 1 will now be modified to include an inverse relation of occurrence probability with sunspot number.

The relation between occurrence probability, D_E and sunspot number (SSN) can be expressed as

$$OP = A \cdot P_{D_E} \cdot P_{SSN} \quad (3-3)$$

where P_{SSN} is given by

$$P_{SSN} = \frac{(250 - SSN)}{250} \quad (3-4)$$

and P_{D_E} is the same as in Model 1. The relation between P_{SSN} and sunspot number is shown in Figure 3.45. Figure 3.46 is an example of the curve fit setting the constant of proportionality, A , equal to 0.23 for all three sections. The influence of solar activity on occurrence probability was first recognized in the data from the late 1980s but using the sunspot number to adjust our fit has improved the fitting over all three sections of the data set. This model now matches the data in section 3 quite well and also matches the low occurrence probability points around 1970 better than the first model now that the sunspot number is included in the fit. The model appears to overcompensate for the drop in occurrence probability in the late 1970s.

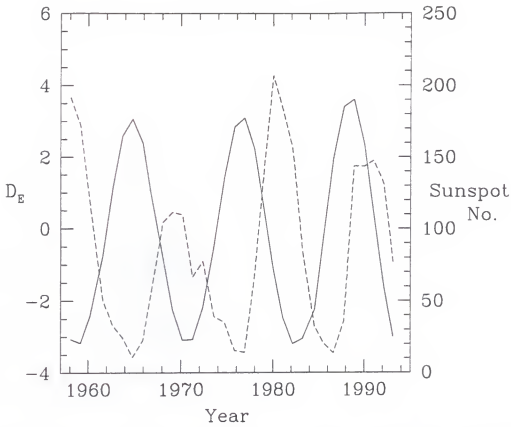


Figure 3.44: A comparison of the time variations in seasonal averaged sunspot number (dashed line) and D_E from 1957–1994.

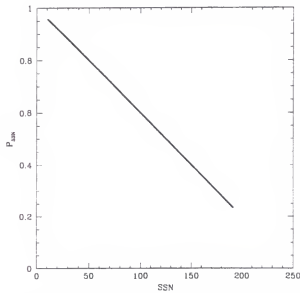


Figure 3.45: P_{SSN} for sections 1, 2 and 3. P_{SSN} is the probability factor which expresses the sunspot dependence of the occurrence probability.

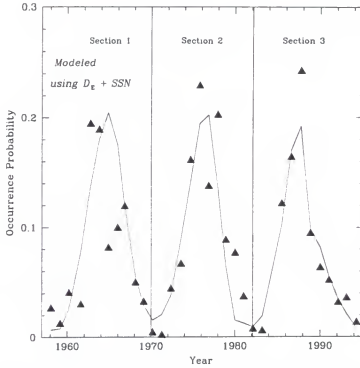


Figure 3.46: Model 2a of the occurrence probability for the 18 MHz non-Io-A source. The constant of proportionality is equal to 0.23 for all three sections. The triangles indicate the observed points.

3.6.3 Model 2b: Same as Model 2a Except for Assumed Decrease in OP at High D_E

The relationship between occurrence probability and D_E used in Model 1 and 2a is maintained in Model 2b in the fit to section 3 where no obvious notch is seen. For sections 1 and 2 the notch is now accounted for by assuming a drop in the occurrence probability for $D_E > 2.7^\circ$. Figure 3.47 shows the probability factor P_{DE} for sections 1 and 2. P_{DE} is given by

$$P_{DE} = \frac{1}{6.7}(D_E + 4), \quad D_E \leq 2.7$$

$$P_{DE} = \cos\left(\frac{\pi}{2}(D_E - 2.7)\right)^3, \quad D_E > 2.7 \quad (3-5)$$

The fit now accounting for D_E and sunspot number as well as a notch in sections 1 and 2 is shown in Figure 3.48. Including the sunspot number in the fit allows for a degree of asymmetry in the occurrence probability peaks although it is not a perfect match to the observed points. The occurrence probability tends to be slightly higher before the “notch”

than after. If the constant of proportionality is allowed to vary some improvement can be made to the fit, an example is shown in Figure 3.49.

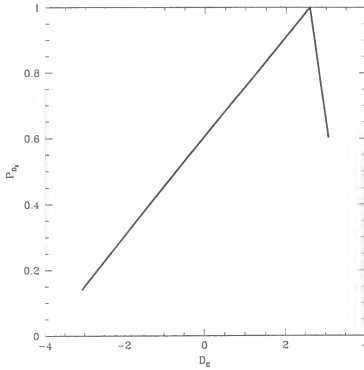


Figure 3.47: P_{DE} for sections 1 and 2. The drop in probability at $D_E > 2.7$ is used to model the “notch” seen during the maximum occurrence probabilities.

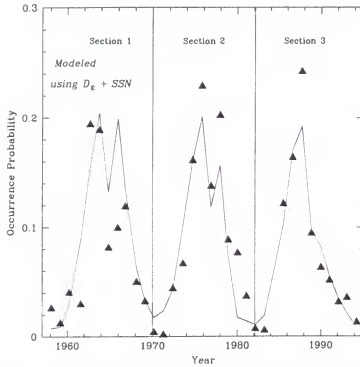


Figure 3.48: Model 2b of the non-Io-A occurrence probability at 18 MHz. The constant of proportionality is equal to 0.23 for all three sections. The triangles indicate the observed points.

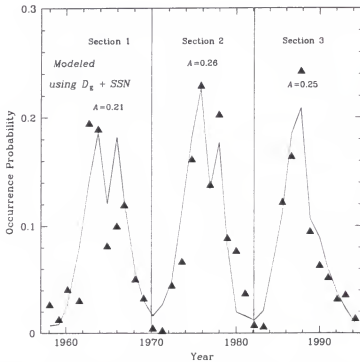


Figure 3.49: Model 2b of the non-Io-A occurrence probability at 18 MHz now allowing the constant of proportionality, A , to vary between sections. The value of A for each section is shown. The triangles indicate the observed points.

3.6.4 Model 3: OP is Proportional to Source Width

Occurrence probability is proportional to the length of time in which the DAM emission beam is pointed towards Earth. A wide rotating emission beam will be detected for a longer time as it sweeps past Earth than would a narrow beam. It is to be expected therefore that occurrence probability should be correlated with source width. Figure 3.19 illustrates clearly the drastic change in source width that occurs with D_E . Given a relationship between occurrence probability and source width similar to that expressed in Equation 3.1 namely,

$$OP = A \cdot P_{Width} \quad (3-6)$$

we use P_{width} to describe the dependence that occurrence probability has on source width. P_{width} is simply the source width divided by the maximum source width in that section of data. Figure 3.50 is a model of the occurrence probability based solely on source width. Figure 3.51 uses both source width and sunspot number to model the occurrence probability. There is a gap in the data in the early 1970s and early 1980s where a clear determination of source width could not be made. The fit for this model does not appear to be as good as that for D_E but an interesting point in this model is that the notch appears naturally to occur at the high occurrence probability peak in all three sections. The fact that the model fits as well as it does provides insight into the non-Io-A emission beam. Assuming occurrence probability would simply be equal to the source width is a sound first approximation. In this model we assume the beam will be uniformly active from the time Earth enters the source until the time it leaves. The occurrence probability is likely to be higher in the center of the beam cross section than towards the edges. Another reason that the fit might be poor is due to the inability to determine accurate source widths during seasons with little data or when the sources could not clearly be resolved. Despite

these assumptions and errors it appears from this model that most of the D_E effect on the occurrence probability is geometrical and due to changes in the width of the beam.

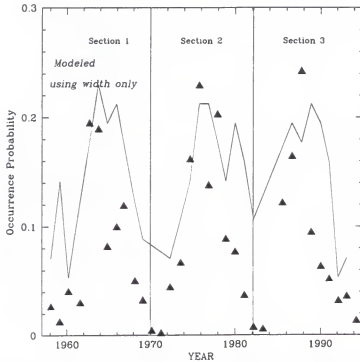


Figure 3.50: Model 3 of the non-Io-A occurrence probability based on the source width. The constant of proportionality is 0.23. The triangles indicate the observed points.

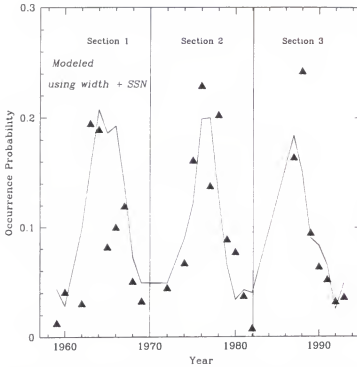


Figure 3.51: A model of the non-Io-A 18 MHz occurrence probability based on source width and sunspot number. The constant of proportionality in all three sections is 0.23. The triangles indicate the observed points.

The notch seen in sections 1 and 2 of Figure 3.41 was not visible in section 3 of the figure. Our model 2a could not fit section 3 if a notch was assumed to be present but simply hidden. The first mention of a “notch” in the UFRO data set was in the dissertation of St. Cyr [1985]. Evidence of this notch in other data sets is seen in Figure 7.13 of *Physics of the Jovian Magnetosphere* [Carr et al., 1983] where data from the University of Colorado at 7-40 MHz and from NASA observing stations at 16.7 MHz is plotted versus time. St. Cyr found from plotting the ratio of the amount of right-hand to left-hand non-Io-A emission that during the period of highest D_E this ratio peaked. In other words, the amount of left-hand activity had fallen relative to the amount of right-hand activity. If the left-handed bursts and right-handed bursts detected in the non-Io-A source were beamed in slightly different directions then the drop in left-hand polarized emission could be due to Earth moving out of that component of the beam which is

left-handed. At the most extreme positive range of D_E there appears to be a turn towards lower longitude in the non-Io-A peak shown in Figure 3.17. This could be evidence for a narrowing of the non-Io-A source at the highest D_E . This can be explained by assuming that when Earth is at its highest Jovicentric declination that it begins to intercept radiation from just north of the beam maximum. That is, the beam maximum for the non-Io-A source is detected when Earth is at about a D_E of 2.7° .

3.6.5 Is There a Solar Effect on DAM?

The Sun can influence the detection of Jovian decametric radiation by changing the local observing conditions, changing the density of plasma in the interplanetary medium and by changing conditions at the DAM source. Researchers have reported positive correlations of DAM with the magnetic sector structures in the solar wind, solar wind ram pressure and solar wind density. All of these correlations were found in short-term (less than one month) variations of the occurrence probability of the non-Io-related sources [Barrow, 1978, Terasawa *et al.*, 1978, Barrow *et al.*, 1986]. A study of the correlation between long-term (years) variations in the Jovian decimetric (DIM) emission and solar activity found a positive correlation with solar wind ram pressure with a lag time of 2 years [Bolton *et al.*, 1989]. Our model assumes little to no lag time exists between changes in solar activity and DAM activity. Figure 3.52 illustrates the change in occurrence probability with year for the non-Io-A source. The dashed line shows the occurrence probability value 12 years (one D_E cycle) earlier. The large drop in occurrence probability after 1987 coincided with a sharp rise in the sunspot number. The notch, if present would explain the decrease in occurrence probability in 1989 but the peak expected in 1990 never occurred rather the probability continued to drop.

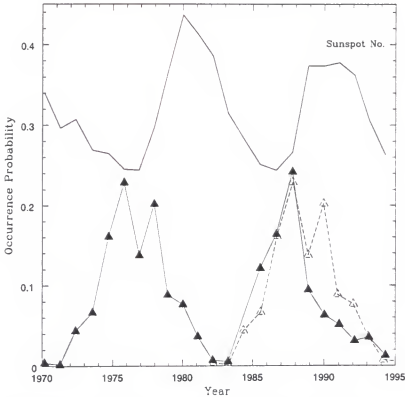


Figure 3.52: A superposition of the occurrence probability data from the 1970s on the occurrence probability data of the 1980s (12 years later). The dashed line illustrates that the occurrence probability during the declining phase of the 1970s was higher than that seen in the late 1980s and early 1990s. This drop in occurrence probability may be related to the sharp rise in solar activity at the time.

If there is a solar influence on long-term variations in DAM it may effect the beam geometry or the emission source or both. A change in the *beam geometry* means that the amount of activity may or may not have changed but the beam has changed its orientation with respect to the ground-based observer and therefore the observer sees a change in the amount of emission. A change at the *emission source* would mean that the activity of the source has changed. There are several characteristics of the Sun and the solar wind which vary with the solar cycle. Of these some are more likely to influence the beam geometry while others may influence the emission source; not all of these characteristics are in phase with sunspot number.

The dynamic or ram pressure of the solar wind, for example, has been found to have a minimum at solar activity maximum. The peak in pressure occurs about 2 to 3 years after solar maximum [Schwenn, 1990, Richardson *et al.*, 1995]. The solar wind ram pressure and the occurrence probability are both falling after 1987. One possibility is that the field lines along which the emission cone is aligned are moving in the sunward direction due to the reduction in solar wind pressure. This movement for a cone in the northern hemisphere may allow ground based observers to see a section of the beam farther to the north than usual, well into the notch mentioned earlier. During years of highest D_E in the 1964 and 1976 seasons the occurrence probabilities dropped, but with the change in orientation of the cone due to the decreased ram pressure the drop in 1988 is even larger. The D_E values reached in the years from 1987 to 1989 were actually about 0.5 degrees higher than during the previous D_E maximums in the 1960s and 1970s. These higher than normal D_E values and the emission beam oriented such that ground-based observers intercept the beam at a higher than normal latitude may combine to explain the drop in occurrence probability. A problem with this model is that when the solar wind pressure peaked in about 1991 the beam should have been pushed back and ground-based observers should have intercepted the peak again. This did not occur. The peak should have been seen in 1990, by this model the peak may have appeared later than expected but it should have appeared.

The paper by Richardson *et al.* [1995] shows the standard deviation of the solar wind ram pressure follows the sunspot number more closely than the average ram pressure although during solar maximum there is more scatter in the data. One cause of a higher standard deviation in the pressure is an increase in shock fronts in the solar wind. Terasawa *et al.* [1978] and Kennedy [1976] speculate that shocks from the collision of fast and slow solar wind streams may enhance the non-Io-related emission source. The

Jovian magnetosphere however may have a characteristic time constant in which too many shocks in succession may have less of an effect on the DAM than more widely spaced shocks [Kennedy, personal communication]. The high rate of shocks encountered during the solar maximum may therefore reduce the amount of activity seen in this period. Another possible means by which the Sun may influence the DAM emission source is by way of UV photons. A good correlation has been found between sunspot number, 10.7 cm flux and the core-to-wing ratio of the Mg II *h* and *k* lines, an index of solar UV flux [Heath and Schlesinger, 1986]. The UV flux would likely increase the electron number density of the Jovian ionosphere, similar to what occurs on Earth. Theories proposed to explain the DAM emission mechanism require electron number densities within a narrow range. The increased number densities may have the effect of saturating the emission source.

CHAPTER 4

SUMMARY AND CONCLUSIONS

This study of over 30 years of decametric observations has been a process of winnowing the wheat from the chaff. The chaff includes such bothersome details as changes in galactic background level, changes in the distance from the source and occasional modifications of the radio telescope system itself. Efforts at correcting for these effects and others had yielded, by the end of Chapter 2, a set of galactic-background-limited occurrence probabilities and average flux densities. Chapter 3 presented what had been gained from the effort, a clear indication of periodic behavior and general trends in some aspects of the decametric emission, somewhat less certain periodicities in other parts and a few parts that remained nearly constant over the entire span of observations.

The non-Io-A source is confirmed to be strongly influenced by D_E . The occurrence probability and the average flux density of the source both showed evidence of a D_E effect though the occurrence probability was found to be a more reliable indicator of this effect. Studies showing a D_E effect in source width are also confirmed. The paper by Carr *et al.* [1970] showed a widening non-Io-A source mostly due to the high CML edge; the low CML edge was virtually independent of D_E . This figure for the non-Io-A beam has been confirmed with the addition of data from over two additional orbits of Jupiter about the Sun. Hypothesis tests using Spearman's rank correlation coefficient of the null hypothesis of no D_E dependence were performed. The occurrence probability of non-Io-A at 18, 20 and 22 MHz all showed sufficient evidence of a D_E dependence to reject the null hypothesis at the 95% confidence interval. The CML peak, midpoint

and edges of the non-*Io-A* source were tested and except for the low CML edge were all found to show a D_E dependence.

From modeling results, the change in source width was found to be one of the primary reasons for the long-term variations in occurrence probability. The D_E effect is therefore primarily a geometrical effect caused by changes in the beam cross section seen from Earth. Improvements in our model came from including a factor based on the yearly averaged sunspot number. This factor served to diminish the modeled occurrence probability and was especially effective in modeling the drop in occurrence probability noted in the mid to late 1980's. The solar activity cycle appears to play a secondary role in influencing the long-term variations of the Jovian decametric activity, at least for non-*Io-A*.

A "notch" seen in plots of occurrence probability versus time at the points of maximum D_E is confirmed. Figure 4.1 is a polar plot of non-*Io-A* occurrence probability and D_E over 39 years. The general trend in occurrence probability is to increase with D_E . At D_E values greater than about 2.7° however a drop in occurrence probability is seen. The latitude range available to ground-based observers in sampling the non-*Io-A* emission beam appears to take it just north of the beam maximum. Over the span of the UFRO data, Earth has made about 6 sweeps in latitude through the beam. The scatter in the polar plot could be due to changes in the orientation of the beam as well as to changes in the emission source over this period.

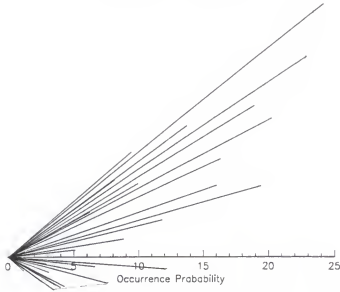


Figure 4.1: A latitudinal slice through the non-Io-A emission beam based on data at 18 MHz from 1957–1994. An envelope is drawn around the points illustrating a possible shape to the beam. The dashed line represents the upper edge of the beam that is sampled during that time in which Earth is in the notch as described in the text.

A search for D_E effects in the other decametric sources has turned up similar though generally not as pronounced influences. The D_E dependence of the occurrence probability of the major DAM sources was studied using Spearman's rank correlation coefficient. A listing of the DAM sources in terms of this coefficient is (in order of decreasing D_E dependence), non-Io-A, non-Io-C, Io-A', Io-B, Io-C and Io-A. The Io-A and Io-A' sources, like the non-Io-A source, showed little to no dependence on D_E in the low CML edge of the source but strong dependence in the high CML edge. The Io-B source shows a dependence on D_E in both the low and high CML edges. The Io-B and Io-C sources show strong D_E dependence in Io-phase as well. Using nearly 40 years of data from the University of Florida Radio Observatory, a uniform set of source boundaries were determined, refining the CML and Io phase locations of the major sources. The Io-B source was also found to display recurrent features in CML-Io phase plots, confirming several previous papers. The significance of these features is still not entirely clear.

As reported by various authors and confirmed in Chapter 3 of this study, D_E influences the phase of Io at which DAM is first detected and at which it ceases for several of the DAM sources [Lecacheux, 1974, Thieman *et al.*, 1975, Bozyan and Douglas, 1976, Boudjada and Leblanc, 1992]. Desch [1978] described the influence D_E has on the Io phase of the DAM sources by defining β , the angle between the magnetic field vector at the source and the direction to the observer (Earth). When β is equal to the cone opening angle the emission is beamed towards Earth. When D_E changes, the direction of the observer changes, and for a particular cone, β may no longer equal the cone opening angle. The cone from which the radiation is most likely to be detected as D_E increases is one at a longitude farther from the Earth-facing longitude. The drift is toward smaller Io phase for the Io-B and Io-C sources. Desch found that the degree and the sense towards which the Io-B and Io-C sources drift in Io phase over the range of D_E is consistent with his model. Chapter 3 reports no conclusive evidence for an Io-A dependence on D_E in Io phase. Figure 4.2 illustrates with a simple geometrical drawing how the Io phase of the Io-B source may be influenced by D_E . Over the range of D_E , represented by the vertical bar in the figure, the particular cone which intercepts Earth will change. Cones 1, 2 and 3 are represented by circles with their labels located at the centers of each circle. Cone 1 is located at a higher Io phase, than cone 2 and 3 and intercepts Earth at a lower D_E , represented by the number 1 next to the vertical bar. Io phase increases towards the right in the figure. Cone 2 is at a slightly lower Io phase and intercepts Earth at a slightly higher D_E .

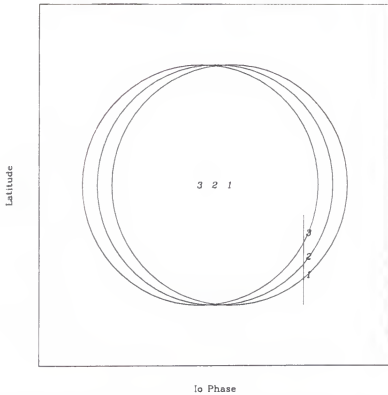


Figure 4.2: An illustration, not to scale, of the effect that D_E has on the Io-phase of the Io-B source. Cones at progressively lower Io phase intercept Earth at higher D_E . The D_E range is represented by the vertical bar and Io phase is increasing towards the right.

The solar effect believed responsible for the premature drop in occurrence probabilities in the late 1980s could be due to a variety of different characteristics of the Sun which vary with period roughly equal to the solar cycle. The Sun could alter the DAM by changing the beaming geometry or the amount of activity at the source or both. Variations in the solar UV flux, the solar wind ram pressure and the standard deviation of the solar wind ram pressure were discussed as possible means by which the Sun could influence the DAM. This list is not exhaustive and although some suggestions on how each of these factors may influence the DAM were presented it is still not clear which if any of these suggestions are the correct ones. This solar effect has been brought to our attention by the unexpected early rise in sunspot number with respect to D_E that occurred in the last 10 years. Previous to this, the secondary influence of the Sun could not be

separated from the primary D_E influence. More data during this unusual period will help to confirm whether this solar effect really exists.

Another free parameter in this study of long-term variations of the decametric emission is the role of volcanic activity on Io. The region around Io's orbit at about 6 Jovian radii is filled with a complex mixture of neutral and ionic species of Sodium, Potassium, Sulfur and Oxygen. The source of this material is Io itself. This volcanically active body is rich in the material found to make up the torus but the exact process by which Io injects these atoms into the torus is still uncertain. The degree to which volcanic activity influences the DAM is unknown. Some insight into the relationship between volcanic activity and DAM may be gained from a study of observations made at the Infrared Telescope Facility in support of the Galileo mission. This is a program to monitor IR hot spots on Io. Another program running coincident with this one is an Io Plasma Torus monitoring program at Lick Observatory. A correlation study between these data sets and the UFRO data sets might be fruitful.

The Voyager spacecraft on their flyby mission to Jupiter were able to measure DAM at higher Jovian latitudes than Earth. The Voyager 2 spacecraft approached Jupiter at a latitude of approximately 7° while Voyager 1 approached Jupiter at about 3.5° . Barrow [1981] and Maeda and Carr [1984] note that the longitude of the non-Io-A source from the Voyager spacecraft data are consistent with an extrapolation of the D_E effect to these higher latitudes. There is no report of any tapering of the non-Io-A beam as reported in this dissertation. St. Cyr however notes that the drop in left hand emission at 18.4 MHz detected by both Voyager spacecraft and reported in a paper by Alexander *et al.* [1981] might be confirmation of the effect seen in the UFRO 18 MHz polarimeter data in 1976. Currently, the Wind spacecraft is detecting DAM over the frequency range of 2–14 MHz [Kaiser and Garcia, 1996]. If it survives another 10 years it will be able to

study the changes in DAM over the entire range of D_E . This long-term monitoring over a wide range of frequencies may help resolve what variations are due to the geometry of the emission beam and what are due to variations intrinsic to the source.

APPENDIX A

A SAMPLE CALIBRATION OF THE YAGI ANTENNA SYSTEM

Calibration of Jupiter radio bursts is done by matching the antenna temperature, T'_A , at the calibration point to the temperature of a noise standard, T'_N . The signal coming from both of these sources is assumed to have been attenuated slightly by line losses. The line loss in decibels from the active element of the antenna to the calibration point is given as L_l and the line loss from the noise standard is L_c . There may also be a preamplifier in the line coming from the antenna which may add a gain of G decibels. At the calibration point the observer will adjust an attenuator in the line coming from the noise standard until

$$T'_A = T'_N. \quad (\text{A-1})$$

The antenna temperature at the calibration point is given in terms of T_A , the temperature at the active element of the antenna by

$$T'_A = T_A 10^{\frac{(-L_l + G)}{10}} \quad (\text{A-2})$$

and the noise temperature of the standard at the calibration point is given in terms of T_N by

$$T'_N = T_N 10^{\frac{(-D - L_c)}{10}} \quad (\text{A-3})$$

where D is the attenuation in decibels inserted in the line by the observer. Equating the two expressions and solving for T_A we get

$$T_A = T_N 10^{\frac{(L_l - L_c - G - D)}{10}}. \quad (\text{A-4})$$

As an example, the galactic background levels for the 18 Yagi before and after the Jupiter radio storm of June 1, 1987 had a deflection on the chart recorder of 15. From the calibration done after the storm, the corresponding decibel attenuation of the noise standard necessary to produce a deflection of 15 is 35.1 decibels, the value of D . The line losses from the antenna to the calibration point are given in tables A.2 and A.3. In 1987, L_l was 6.8 decibels, L_c was assumed to be zero because the calibration was done in the observatory so there was very little cable between the noise standard and the calibration point. There was no preamplifier on 18 Yagi in 1987 so G is zero as well. The antenna temperature of the galactic background from equation A.4 is

$$T_{AGB} = T_N 10^{\frac{(6.8-0-0-35.1)}{10}} \quad (\text{A-5})$$

The noise source used in the calibrations is an HP461A amplifier which has a noise temperature of 62.7×10^6 Kelvin. The antenna temperature of the galactic background is 93,147 Kelvin. During one five minute interval of the storm a Jupiter burst was recorded with a deflection of 29. The noise standard matches this deflection with an attenuation of 31.7 decibels. The antenna temperature for this burst T_{AJ+GB} is 202,596 Kelvin. This temperature contains a contribution due to Jupiter as well as the galactic background. The interpolated galactic background temperature for this storm is equal to the galactic background at the beginning of the storm. The difference between the two temperatures is equal to the galactic background subtracted antenna temperature, T_{AJ-GB} .

The flux density of the Jupiter burst is given by

$$S = \frac{2kT_{AJ-GB}}{A_e} \quad (\text{A-6})$$

where k is Boltzmann's constant and A_e is the effective area of the 18 Yagi antenna. The A_e values for the Yagi antennas used in this study is given in Table A.1. The flux density for the Jupiter burst is 8.6×10^{-21} Watts / m² Hz. Usually the flux density is

expressed in terms of Janskys where 1 Jansky = 10^{-26} Watts / m² Hz. The flux density is then 8.6×10^5 Janskys.

Table A.1: Antenna characteristics for the 18 MHz , 20 MHz and 22 MHz Yagi antennas

Yagi	Frequency (MHz)	Number of Elements	Effective Area (m ²)
18	18.0	5	351.0
20	20.0	4	218.0
22	22.2	5	229.0

Table A.2: Line losses and gains and antenna failures 1965–1985. Losses and gains are in units of decibels (dB).

Year	Antenna	L _l	L _c	G	Comments
1967-90 typical	18Y	6.8	0	0	Losses and gains for 18Y and 20Y based on measurements taken on Dec 6, 1988.
	20Y	5.5	0	0	
	22Y	3.5	0	0	
1965-67	18Y	4.8 est.	0	0	Bivens Arm
1970	18Y	9.8	0	0	Dec. 7-18, -3 dB hybrid ring
1982	22Y				Fixed @ T-3 Jan. 5-20
1983	18Y				Fixed @ T+5 May 1-3, T+1 May 6-16, T-3 May 18
1985	18Y	est.		est.	Apr. 2-Jun. 5 -3dB hybrid ring, Jul. 5-Sep. 12 +10 dB preamp & -3 dB hybrid ring, fixed @ T-3 Apr. 24-30
	22Y				Fixed @ T-1 Aug. 21-24, @ Trans. Aug. 25-26, @ T-0.6 Aug. 27-29, @ T+1.5 Sep. 4-25

Table A.3: Line losses and gains and antenna failures 1986–1994

Year	Antenna	L_l	L_c	G	Comments
1986	22Y				Fixed @ T+2.5 Jul 30-31 @ Trans. Oct. 15-19? @ T+2.5 until end of season?
1987	18Y				Fixed @ T-4 May 26-Jun. 3
	20Y				Fixed @ Trans. Aug. 12 @ T+1 Aug. 25-27
1988	22Y				Fixed @ T+7.5 Sep. 17-19 @ T+4 Sep. 20
1990	18Y	5.5			Fixed @ T-2 Dec. 1-2,
	20Y	4.5			Lines replaced for 18Y & 20Y
	22Y				Fixed @ T-3 Oct. 10?- Nov. 30, @ T+1 Dec. 3-11 @ T-5 Dec. 12—Feb. 1?
1991	18Y			13.0	Fixed @ T-2 Nov. 22
	22Y				Fixed @ T-5 Jan. 1-Feb. 1? @ T+5 Mar. 15, @ T-4 Nov.22
1992	18Y		3.0	13.0	Fixed @ T+5 Feb. 9, G = +13 dB until Apr. 30? Nov. 5 calibration done in field upstream of preamp.

APPENDIX B TESTS FOR D_E DEPENDENCE

An assumption that needs to be made in order to interpret the value of a correlation between n pairs of points from two sets of data, X and Y , is that the data are both random samples from a normally distributed population. In these cases a linear correlation coefficient such as Pearson's r [Mendenhall and Scheaffer, 1973] is commonly used and is given by

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2}}. \quad (\text{B-1})$$

Pearson's r coefficient takes on values from +1 for a positive correlation where all points lie on a straight line with positive slope and -1 where all the points lie along a line of negative slope. An r value of 0 implies no correlation exists between the two sets of data. For determining correlations between D_E and source longitudes or occurrence probability a problem arises in that the data are not normally distributed so interpretation of Pearson's r coefficient becomes unclear.

Another measure of correlation which does not depend on the distribution of X and Y is Spearman's rank correlation coefficient. In this method for N pairs of measurements each X_i is replaced by its corresponding rank among the N values. The Y values are also replaced by their ranks. If R_i represents the rank of the i th element of X and S_i is the rank of the i th element of Y then the Spearman's rank correlation coefficient, r_s

[Press et al., 1992] is

$$r_s = 1 - \frac{6 \sum_{i=1}^N (R_i - S_i)^2}{N^3 - N} \quad (\text{B-2})$$

Spearman's r_s takes on the same range of values as Pearson's r correlation coefficient.

A sample computation of Spearman's r_s is given below.

non-lo-A at 20 MHz					N = 27
D _E	rank of D _E , R	Oc. Prob.	rank of Oc. Prob., S	(R - S)	(R - S) ²
3.06	24	0.0248	12	12	144
2.38	22	0.0391	18	4	16
1.01	17	0.0702	20	-3	9
-0.84	12	0.0187	11	1	1
-2.25	8	0.0149	9	-1	1
-3.09	3	0.0029	2	1	1
-3.07	4	0.0022	1	3	9
-2.18	9	0.0068	7	2	4
-0.47	13	0.0473	19	-6	36
1.44	18	0.0951	24	-6	36
2.84	23	0.1308	26	-3	9
3.09	25	0.0799	22	3	9
2.22	20	0.0969	25	-5	25
0.66	16	0.0339	16	0	0
-1.10	11	0.0299	13	-2	4
-2.47	7	0.0166	10	-3	9
-3.19	2	0.0052	4	-2	4
-3.05	5	0.0062	6	-1	1
-0.32	14	0.0755	21	-7	49
1.94	19	0.0823	23	-4	16
3.40	26	0.1574	27	-1	1
3.60	27	0.0334	15	12	144
2.34	21	0.0327	14	7	49
0.45	15	0.0350	17	-2	4
-1.57	10	0.0048	3	7	49
-3.00	6	0.0075	8	-2	4
-3.70	1	0.0054	5	-4	16
$\sum (R - S)^2 =$					650

$$r_s = 1 - \frac{6(650)}{27^3 - 27} = 1 - \frac{3900}{19656} = 0.8016 \quad (\text{B-3})$$

The Pearson's r coefficient for the same set of data is 0.812. In this instance relaxing the restriction of normality in the use of Pearson's r does not introduce a significant error.

The goal of this study is to determine whether the two populations from which the measurements were taken are also correlated. In other words, can we reject the null hypothesis of an r_s value of 0 for the population in favor of the alternative hypothesis that $|r_s| > 0$ for the population given the correlation measured for the sample. In order to test the significance of the r_s value we must know how r_s is distributed for all possible rankings of X against an arbitrary ranking of Y . This will be a two-tailed test if we do not assume a positive or negative correlation exists in the population. For $N > 35$ a normal approximation can be used for the frequency distribution of r_s . For $19 \leq N < 30$ the Student's t distribution can be used with the number of degrees of freedom, $df = N - 2$ [Kendall and Gibbons, 1990]. The test statistic for a Student's t distribution is

$$t = r_s \sqrt{\frac{N - 2}{1 - r_s^2}} \quad (\text{B-4})$$

For the value of r_s computed above and 25 degrees of freedom the test statistic, t , is 6.704. A table of critical values of the Student's t shows that for a two-tailed test the probability is less than 1% that the population that these two sets of measurements were drawn from is uncorrelated given the rank correlation coefficient determined above. The headings used in Chapter 3 to classify the confidence of a D_E dependence of each of the sources was based on these significance tests. Any test which showed a confidence level greater than 95% for correlation between the two populations was deemed a very likely candidate for a D_E dependence. Data in which the confidence was between 80 and 95% was deemed a possible candidate for D_E dependence. No conclusion on D_E dependence could be reached for those data in which there was less than an 80% probability for correlation.

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BIOGRAPHICAL SKETCH

Leonard N. Garcia was born on August 21, 1967, in Miami, Florida to Leonardo and Marilyn Garcia. Leonard has two younger sisters, Rosie and Jenny. Leonard grew up watching Star Trek and Star Wars and looking back finds that his interests have always been about the same. Leonard plays no sports nor does he know how to play any musical instruments. He attended Southwest Miami High School and received his B.S. in physics from Florida International University. He moved to Gainesville in 1990 to begin his graduate studies at the University of Florida. On Easter of 1994 Leonard became a Catholic and is a Knight of Columbus. Leonard does enjoy good jokes and has been known to watch Saturday morning cartoons. Leonard has read the *Lord of the Rings*, the *Chronicles of Narnia*, and some science fiction from Isaac Asimov and Arthur C. Clarke. He enjoys building models and studying his family tree. His favorite dish is a palomilla steak with chopped onions and a bit of parsley on top and a side of platanos maduros and moros. Finish it off with a flan and cafe', ¡Que Rico! Leonard found Miss Sarah Matestic in the mountains of Kentucky (or did she find him?) and plans to share his life with her.

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Professor of Astronomy and Physics

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Associate Professor of Astronomy

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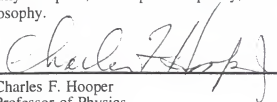
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This dissertation was submitted to the Graduate Faculty of the Department of Astronomy in the College of Liberal Arts and Sciences, and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1996

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